

Energy Research and Development Division  
**FINAL PROJECT REPORT**

# **Central Valley Research Homes Project**

**California Energy Commission**

Edmund G. Brown Jr., Governor

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## PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

*Central Valley Research Homes Project* is the final report for the Central Valley Research Homes project (Contract Number 500-10-014) conducted by Bruce A. Wilcox, P.E. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at [www.energy.ca.gov/research/](http://www.energy.ca.gov/research/) or contact the Energy Commission at 916-327-1551.

## ABSTRACT

California's Central Valley region has hot, dry summers and mild winters and its 2.2 million homes across 17 counties consume 22,700 gigawatt-hours of electricity each year. The Central Valley Research Homes Project demonstrated ways to improve energy efficiency in existing homes in the region. The research team set up four unoccupied homes of diverse ages as laboratories to collect data through a set of carefully designed experiments, with heaters and humidifiers simulating human presence. The team developed retrofit packages, including envelope and heating, ventilating, and air conditioning technologies that could achieve 50 percent to 75 percent savings in heating and cooling energy, using techniques that could be cost effective when applied as part of a multi-house optimized retrofit program. Retrofits included:

- Down-sized and advanced air conditioning and heat pump systems.
- Whole house fans.
- Energy efficient ducts, such as ducts buried in attic insulation, duct reconfiguration.
- Attic and wall insulation .
- Air sealing of the attic and ceiling.
- High efficiency windows.

The project was able to decrease cooling energy by up to 75 percent and heating loads in the two older houses by 54 percent. The research suggests that accurate checklists can provide inexpensive guidance for retrofits in existing homes. The cost-effective measures demonstrated in this project could be used in local area direct install programs, which could reach a larger number of homes at a lower cost, contributing to the energy and emissions reduction goals of California.

**Keywords:** air leakage, air sealing, building energy efficiency, California, CBECC-Res 2013, ducts, energy efficiency, energy efficiency retrofits, energy efficiency upgrades, energy simulation, energy modeling, existing buildings, HERS rating, HVAC, IAQ fan, indoor air quality fan, insulation, residential buildings, Title 24, window replacement, ventilation, whole house fan, zero net energy.

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# EXECUTIVE SUMMARY

## Introduction

As California's population continues to grow, more people are moving to homes in the hot, dry inland areas of the state. In the summer these hotter areas require more air conditioning than coastal areas, which increases the state's peak electricity demand and its greenhouse gas emissions. Residential Building Energy Efficiency Standards have been part of California's regulatory landscape since the 1970s and have made substantial impacts on reducing statewide energy consumption. California's existing residential building stock, however, has more than 8.5 million pre-code buildings, representing substantial opportunities for lighting, shell, and mechanical system efficiency improvements.

While these pre-code buildings in the existing home building stock offer a huge opportunity for energy savings, convincing building owners and tenants to make energy efficiency upgrades in existing buildings can be difficult. The Central Valley Research Homes Project explored these opportunities on existing homes in inland Stockton, California, which served as controlled laboratories to test and demonstrate energy efficiency retrofits.

## Project Purpose and Process

As stated before, there is a tremendous opportunity for cost-effective energy savings in California existing homes through efficiency retrofits. This is partially due to the condition of the building stock and also due to the volume of existing homes. The collective energy savings possible is considerably larger relative to new homes built to meet the state's current Residential Building Energy Efficiency Standards. The 2016 Standards are anticipated to save 133 gigawatt hours annually in the single-family sector, and implementing retrofit measures in existing homes statewide would likely provide even greater savings.

The project team tested efficiency and energy technologies in four full-scale homes built in different years in distinct California climates and with a variety of foundation types, sizes, and number of stories. Each home had well-controlled and repeatable indoor conditions.

The homes were named for the streets on which they were located: Grange (built in 1948), Mayfair (built in 1953), Fidelia (built in 1996), and Caleb (built in 2006). Each home was monitored for the first year and the collected energy data was used as a baseline. The project team designed, installed, and tested optimized retrofit packages for each home to determine the actual energy savings and demand reductions. It was anticipated the various cost-effective energy retrofits would save 50 percent to 75 percent of the energy used for home heating and cooling.

Each house had reference heating and cooling systems that were fully contained within the conditioned space except for the condensing units for the air conditioners. These reference systems served as "yardsticks" against which to measure the effects of retrofit measures. The reference systems alternated operation with the homes' existing heating, ventilation, and air conditioning systems every two days.

The retrofits included new high-performance windows; sealing and insulating of ducts; insulation and air sealing; heating, ventilation, and air conditioning equipment improvements and fan motors; insulated roof deck; whole-house fans; and alternate systems including heating, ventilation, and air conditioning zoning and mini-split and multi-split systems.

## **Project Results**

### **Effect of Retrofit Packages on Cooling Loads**

In the first retrofit year the project developed envelope and heating, ventilation, and air conditioning efficiency retrofits that saved an average of 75 percent of the cooling energy in the older three homes (Grange, Mayfair, and Fidelia). These savings were achieved through simple retrofits (ducts, heating, ventilation, and air conditioning, insulation, air sealing, modern windows, and whole house fans). Even the newest home – the Caleb house, built in 2006 under the 2005 Building Energy Efficiency Standards with well-insulated, low-E windows – achieved a 52 percent cooling energy savings.

The cooling kWh reductions from whole house fans were impressive. When these savings were combined with insulation, strategic air sealing, and high efficiency windows, the cooling loads were reduced by 71 percent in Grange and 63 percent in Mayfair, the two older homes with poor insulation, and by 32 percent in Fidelia and Caleb, the two newer homes.

### **Retrofit Package Impacts on Heating Loads**

The envelope retrofits also reduced the gross heating loads in the two older houses by an average of 54 percent. This was the total heat loss of the house. Some of these heat losses were offset by internal gains, while the remainder were offset by the space heating system.

While the envelope retrofits on Fidelia and Caleb reduced cooling consumption, they had minimal or negative effects on the heating loads. In Fidelia the gas furnace was replaced with an electric heat pump. The site energy heating use savings at Fidelia was 85 percent.

### **Ventilation and Ducting**

The Mayfair house had a ventilated crawlspace and presented a special opportunity to reduce the infiltration through the crawlspace and floor. This special retrofit was the most cost-effective measure tested.

Putting the ducts in conditioned space has been the norm for ducted heating and cooling systems for some time, but the Central Valley Research Homes Project has proven that ducts do not have to be in conditioned space to achieve high efficiencies. The two older homes in the project had their attic duct systems shortened, sealed, and super-insulated to achieve results comparable to ducts in conditioned space.

The hot dry air conditioning systems that were installed consisted of reducing duct restrictions and compressor sizes in the four homes and provided a 55 percent increase in the cooling coil airflow. The combination of increased duct efficiency, increased cooling air flow, and increased heat exchange efficiency greatly improved cooling efficiencies and reduced peak energy use in all four homes.



## **Project Benefits**

The results of this project will continue to guide California's Title 24 Building Energy Efficiency Standards to reduce energy consumption in new and existing buildings. It is a proving ground for technologies that reduce both annual kilowatt-hours and peak kilowatt-hours of energy used.

This project has also reduced the uncertainty regarding the installed performance of the new and emerging technologies in the following areas that can save energy in California homes:

- Crawlspace ventilation reduction.
- Whole-house fans.
- Attic air sealing and insulation.
- Wall insulation.
- Single-pane window replacement.
- Heating, ventilation, and air conditioning duct system rebuild.
- Hot dry air conditioning.
- Tile roof repair.

The results of this research suggest that simple, accurate checklists could be used to determine the highest priority retrofits to provide meaningful energy savings and provide inexpensive guidance for retrofits in existing homes.

The measures proven in this project can be used in local area programs to directly install efficiency measures. These programs could reach a large number of homes at low cost, contributing to California's energy and emissions reduction goals.



# CHAPTER 1:

## Introduction

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California's stock of existing homes offers cost-effective opportunities for substantial efficiency retrofits. The large number of existing homes presents a tremendous, collective opportunity for savings that is markedly larger than the savings from new homes built to meet the state's current Residential Building Energy Efficiency Standards. The 2016 Standards are anticipated to save 133 gigawatt-hours (GWh) annually in the single-family sector (Nittler, 2015), and widespread implementation of retrofit measures in existing homes would likely provide even greater savings.

It is important to obtain additional data on the existing homes to understand energy saving opportunities. Most current energy use data comes from utility bill analysis, surveys, and monitoring in occupied homes where the presence and behavior of occupants often makes it more difficult to obtain consistent results. To date, there has been no facility that provides the opportunity to collect detailed data under controlled conditions in older California homes.

### Goals

The Central Valley Research Home (CVRH) Project addressed this data deficit. The project team leased four unoccupied homes in Stockton, California. These served as laboratories where energy use and energy efficiency could be scientifically studied over three years. One major goal was to demonstrate cost-effective energy retrofits that would save 50 percent to 75 percent of the energy used for home heating and cooling. The team designed and installed energy retrofits and carried out experiments to determine the actual energy savings and demand reductions.

This CVRH research was designed to contribute to:

- Developing analytical approaches and optimized retrofit measures for typical existing homes
- Informing local and statewide energy efficiency programs
- Giving homeowners and retrofit program managers more confidence to proceed with home efficiency retrofits

### Partners

This project was supported by the California Energy Commission's Energy Research and Development Division. The research team members were Bruce A. Wilcox, P.E.; John Proctor, P.E., Proctor Engineering Group, Ltd.; and Rick Chitwood, Chitwood Energy Management. Industry partners include Cardinal Glass Industries, 3M, and Green Home Solutions by Grupe.

# Timeline

The CVRH Project began in 2011 and ended in 2015. The project's timeline and main activities is described below.

## **2011: Acquiring Homes**

Project team arranged to lease four typical, unoccupied homes of different vintages in Stockton, California.

## **2012: Conducting Home Energy Rating System (HERS) Ratings and Installing Instrumentation**

The team carried out a complete survey and full suite of diagnostic tests to characterize and document each home's energy features. The team hired multiple HERS researchers to rate each home, and compared their results to each other and to the team's characterizations.

The team installed instrumentation, reference heating, ventilation, and air conditioning (HVAC) systems, and monitoring and control systems provided by Cardinal in each home.

## **2012–2013: Collection of Baseline Performance Data**

The team operated all four houses with as-found energy features for one year to generate baseline data. The as-found and reference HVAC systems were run alternately.

HERS II estimates were compared to measured data and the results were used to develop input rules and simulation revisions to improve the accuracy of HERS II estimates.

## **2013–2014: Installation of First Retrofit Year Packages and Collection of Data**

The team installed retrofit packages for the building envelope (one or more of the following items: insulation, windows, air sealing, cool roof) and HVAC system (one or more of the following items: whole house fans, ducts, air handler fan motors, zone controls, improved energy efficiency ratio, reduced cooling capacity) in each home. Cardinal contributed advanced retrofit glazing systems, an HVAC manufacturer contributed an advanced multi-zone ductless air conditioning system and a division of 3M contributed a cool roof system for testing.

## **2014–2015: Installation of Second Retrofit Year Packages and Collection of Data**

The team operated variable compressor speed heat pumps in three of the houses as the "house system." In the fourth home, the retrofit included removing some constraints on the whole house fan and the installation of a balanced ventilation system to test against exhaust-only and supply-only ventilation.

# CHAPTER 2:

## Research Homes Data Collection Methodology

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### Overview

The project team identified four unoccupied homes in Stockton, California suitable for carrying out the experiments, and arranged to lease the homes and keep them unoccupied for several years. The homes ranged in vintage from 1948 to 2006, and varied in their foundation type, size and number of stories. The energy issues presented by the homes covered the spectrum of typical existing houses in California. Glazing ranged from single-pane steel casement windows to double-pane low-E windows in the newest home. Similarly, ceiling insulation R-value ranged from R-5 to R-30.<sup>1</sup> The quality of air sealing, duct location and insulation amounts, and heating, ventilation, and air conditioning (HVAC) system types and efficiencies provided similar ranges of energy performance issues.

These typical homes provided an opportunity to make a range of retrofits and test their potential for deep energy savings (50 percent to 75 percent). The retrofits included:

- New high-performance windows.
- Sealing and insulating ducts.
- Insulation and air sealing.
- HVAC equipment improvements, fan motors, downsizing.
- Insulated roof deck.
- Whole-house fans.
- Alternate systems including HVAC zoning and mini-split and multi-split systems.

After leasing the homes, the team carried out a complete survey and full suite of diagnostic tests to characterize and document each home's energy features. These characteristics are described in Chapter 3.

The team installed reference cooling and heating systems ("reference system") in each home (Figure 1 and Figure 2). These systems were located completely indoors (except for the air conditioning condensing unit) so that no duct conduction or leakage effects would occur. The reference systems provided a nearly constant "yardstick" throughout the experiments. Each reference system alternated operation with the test HVAC system or "house system" on two-day cycles, providing data on a wide variety of outdoor conditions over a year of operation. Chapter 3 describes the characteristics of the house and reference systems in detail.

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<sup>1</sup> R-Value is a measure of insulation's ability to resist heat traveling through it. The higher the R-Value, the better the thermal performance of the insulation (<https://www.energystar.gov>).

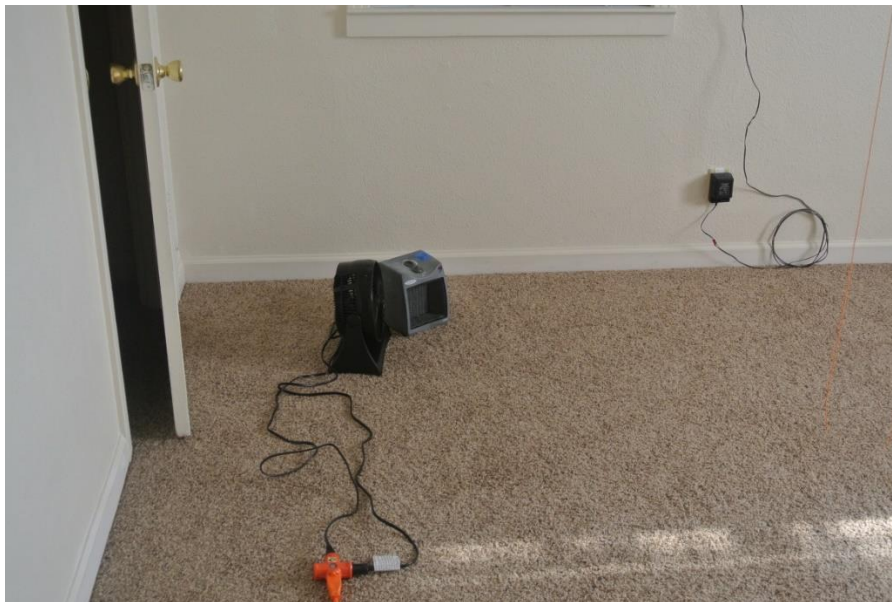
In the summer, the changeover between the house and reference systems occurred at midnight, and in the winter the changeover occurred at 7 a.m. Reference heating systems consisted of electric resistance heaters in every room within the home.

**Figure 1: Reference Cooling Systems Installed Completely Inside the Research Homes**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 2: Reference Heating System – Electric Resistance Heaters in Every Room**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

The research team installed monitoring and control systems in each home. The systems controlled the operation of the HVAC and internal gain systems<sup>2</sup> and allowed for switching between the house and reference HVAC systems. The team heavily instrumented the research homes to provide hour-by-hour and minute-by-minute data. The monitoring equipment also controlled humidifiers and heaters that simulated latent and sensible heat gain from typical occupancy.<sup>3</sup>

**Figure 3: Equipment Used to Simulate Occupants in Research Homes**



The monitored data points were read every 20 seconds and the average (or sum as appropriate) was recorded every minute. The monitored points are listed in Table 1.

**Table 1: Monitored Data Points**

Category	Item
Energy Used	Total House kWh
	House AC Condensing Unit kilowatt-hours (kWh)
	House AC Inside Unit kWh
	House Furnace Natural Gas (cubic feet)
	Reference AC Condensing Unit kWh
	Reference AC Inside Unit (air handler) kWh
	Reference Heating kWh
Occupancy Simulator	Latent kWh
	Sensible kWh
Whole House Fan	Inside-Outside Temperature Differential
	Status (on/off)
Ambient	Outdoor Ambient Temperature (3 locations)

<sup>2</sup> Internal heat gain refers to heat produced by people, lights, and equipment within a building space.

<sup>3</sup> Latent heat refers to moisture or water vapor produced by building occupants and equipment, while sensible heat is generated by internal heat sources (people, lights and equipment); both represent a cooling load for the building.

Category	Item
	Outdoor Ambient Humidity
	Wind Speed
	Horizontal Solar Radiation
Heating and Cooling	Thermostat Set Point
	Active System (House or Reference)
House AC	Evaporator Saturation Temperature
	Evaporator Saturation Temperature (run time average)
	Suction Line Temperature
	Suction Line Temperature (run time average)
	Condenser Saturation Temperature
	Condenser Saturation Temperature (run time average)
	Liquid Line Temperature
	Liquid Line Temperature (run time average)
	Return Air Temperature
	Return Air humidity
	Return Air Temperature (run time average)
	Return Air humidity (run time average)
	Thermostat Call Status (each zone)
	Condensing Unit status (on/off)
	Number of Cycles
House Air Handler	Status (on/off)
	Number of Cycles
House Furnace	Thermostat Call Status (each zone)
	Number of Cycles (each zone)
	Status (on/off)
	Number of Cycles
Reference AC	Supply Air Temperature (each outlet)
	Supply Air Temperature (run time average each outlet)
	Return Air Temperature
	Return Air Temperature (run time average)
	Condenser Saturation Temperature
	Condenser Saturation Temperature (run time average)
	Liquid Line Temperature
	Liquid Line Temperature (run time average)



Category	Item
	Condensate
	Thermostat Call Status (each zone)
	Condensing Unit status (on/off)
	Number of Cycles
Reference Air Handler	Status (on/off)
	Number of Cycles
Reference Heat	Status (each room)
Heating and Cooling	Room Temperatures (each room)
	Garage Temperature
	Attic Temperature
	Temperature (each thermostat)
	Humidity (each floor)
	Temperature (each floor at Humidity Sensor)
	Humidity (run time average each floor)
	Temperature (run time average each floor at Humidity Sensor)
	Thermocouple Reference Temperature (2)
Pressure Differential	Floor
	Ceiling
Slab	Slab Heat Flux (2 Locations)
	Slab Temperature (up to 26 Locations)

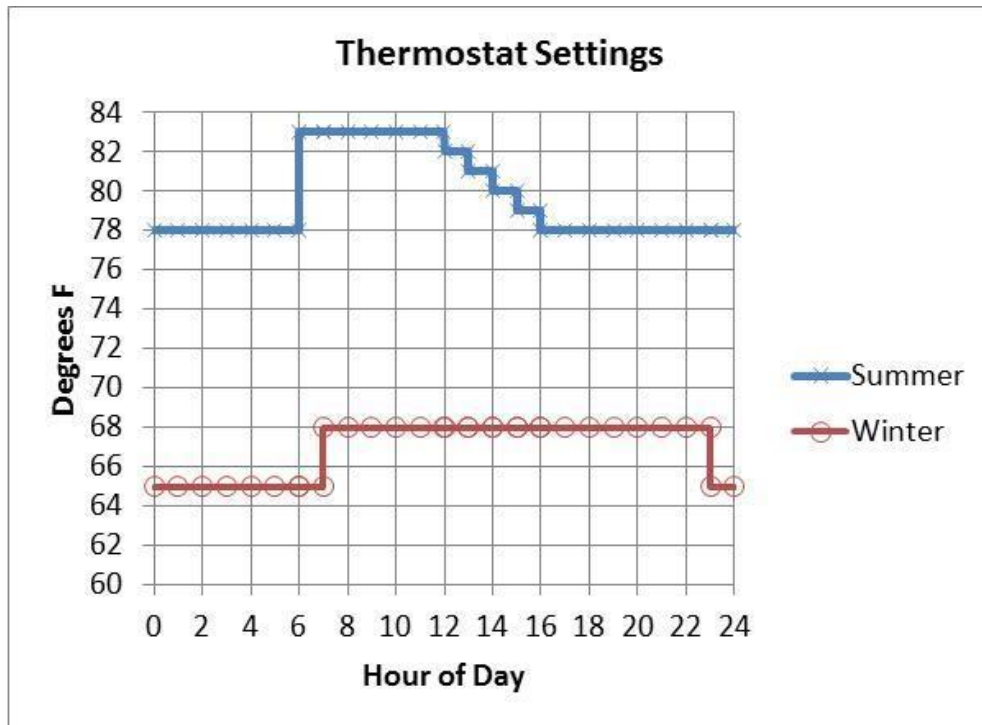
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Occupancy Simulation

Perfectly consistent occupants are impossible to find for a controlled experiment. Therefore, the houses were "occupied" by heaters and humidifiers that were perfectly consistent in adding sensible and latent internal gains. The gains represented the heat produced by occupants, lights, and appliances and were derived from California's Residential Building Energy Efficiency Standards (Title 24, Part 6) as used in the HERS technical manual. The implemented internal gains are detailed in Appendix A.

Consistent thermostat behavior is also impossible with real occupants. For the simulated occupants in this project, the research team used the thermostat settings defined in the Title 24 Building Energy Efficiency Standards. These settings (Figure 4) produced load patterns similar to those for average residences.

Figure 4: Thermostat Settings to Duplicate Average Load Shape



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

# CHAPTER 3:

## Impact of Efficiency Retrofits on Energy Use of Each Home

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This chapter provides details about

- Existing (“baseline”) conditions of each home.
- Reference heating, ventilation, and air conditioning (HVAC) systems installed in each home.
- Specific retrofits made to the building envelope and HVAC systems in 2013 (Retrofit Year 1) and 2014 (Retrofit Year 2).
- Impacts of these retrofits on energy use.

Chapter 4 includes further discussion about results of Retrofit Year 1.

Each house is identified by the street on which it was located – Grange, Mayfair, Fidelia and Caleb. From July 2012 to April 2013, the team operated all four houses with their existing envelopes and HVAC systems to generate baseline data. Analysis of these data provided heating and cooling loads, information about their dependency on outdoor conditions and indoor thermostat settings, as well as data on the efficiency of the existing HVAC system (referred to as the house system to distinguish it from the reference HVAC system).

During this period, the team determined the first retrofit packages for each home, factoring in the energy savings potential and lifecycle costs of alternatives. Installation of the retrofit measures began in spring 2013.

From May 2013 to April 2014, the team installed and commissioned the first retrofit packages for the building envelope and HVAC systems. The packages were designed to achieve 50 percent to 75 percent savings in heating and cooling energy, using techniques that could be cost effective when applied as part of a multi-house, optimized retrofit program.

During the summer of 2013 through the spring of 2014 the team operated the systems under the same internal gain and thermostat schedules as in the baseline year while recording conditions and energy use. As before, the reference HVAC systems and now-retrofitted House HVAC systems alternated every two days. This produced estimates of HVAC system efficiency and the separate the impact of load reductions.

From May 2014 to February 2015, the team installed and commissioned the second set of retrofit measures. These measures included: variable compressor speed heat pumps – chosen due to intense interest in this alternative technology, continuation and expansion of whole house fan parameters as well as additional testing of indoor air quality (IAQ) fan options.

# Grange Home

## Baseline Conditions

Built in 1948, the Grange Avenue house (Figure 5 – Figure 12) is the oldest of the test houses. At 848 square feet it is also the smallest. It is a two-bedroom, single-story rectangular house with slab-on-grade construction. This house had an initial annualized<sup>4</sup> cooling energy use of 1.05 kilowatt-hours per square foot (kWh/ft<sup>2</sup>), which is 42 percent higher than that of Caleb, the newest test house. Grange had an annualized heating energy use of 0.38 therms per square foot, which was 4.8 times the heating energy intensity of Caleb.

**Figure 5: Grange – Exterior**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

The baseline conditions included single-glazed aluminum slider windows (Figure 6), a virtually uninsulated ceiling (Figure 7), and 2 x 3 walls with aluminum foil insulation. There was an 80.5 annualized fuel utilization efficiency (AFUE) 50,000 British thermal units per hour input furnace and 2.5 ton air conditioning (AC) coil in the garage with the ducts in the attic and a 2.5 ton 10.45 SEER 9.5 EER roof-mounted condensing unit.

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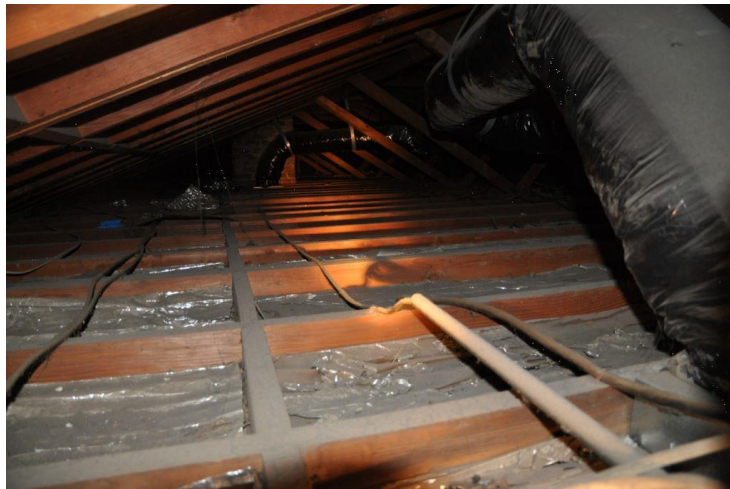
<sup>4</sup> Standardized to 2013 Title 24 Sacramento weather file.

**Figure 6: Grange – Single-Glazed Aluminum Sliding Window**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 7: Grange – Foil Insulated Ceiling and Walls**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 8: Grange – Accordion Foil Insulation in 2 x 3 Walls**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood



**Figure 9: Grange – Fireplace Cavity Before and After Air Sealing**



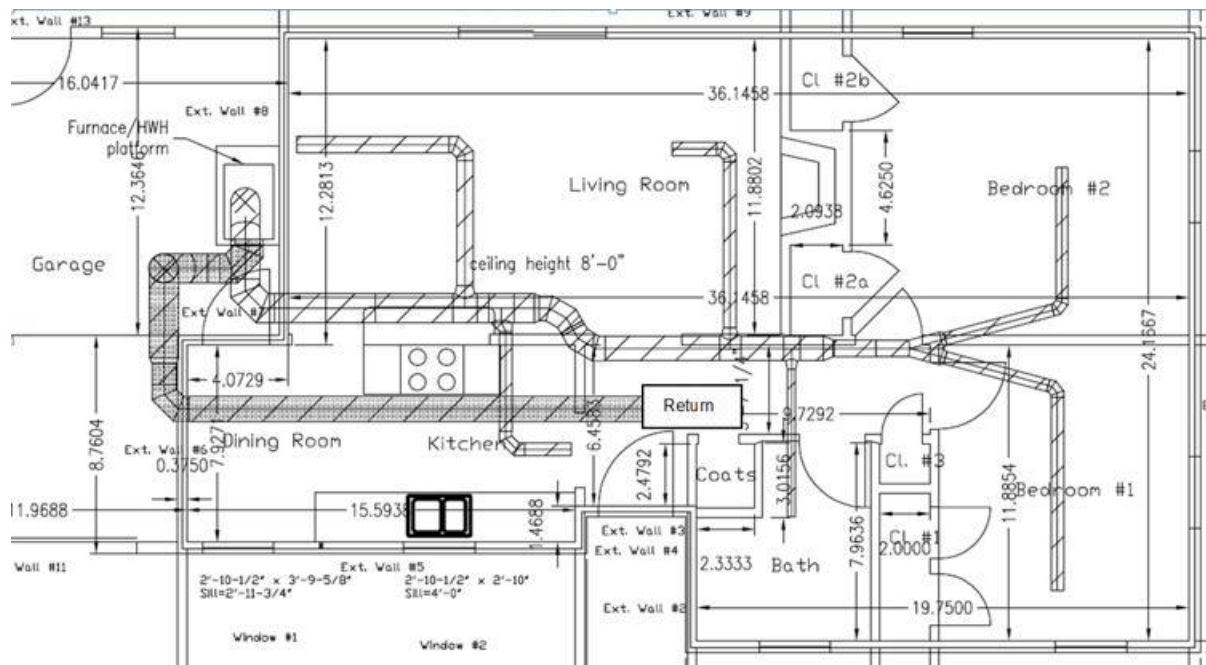
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 10: Grange – Duct Surface Area is 41 percent of Floor Area**



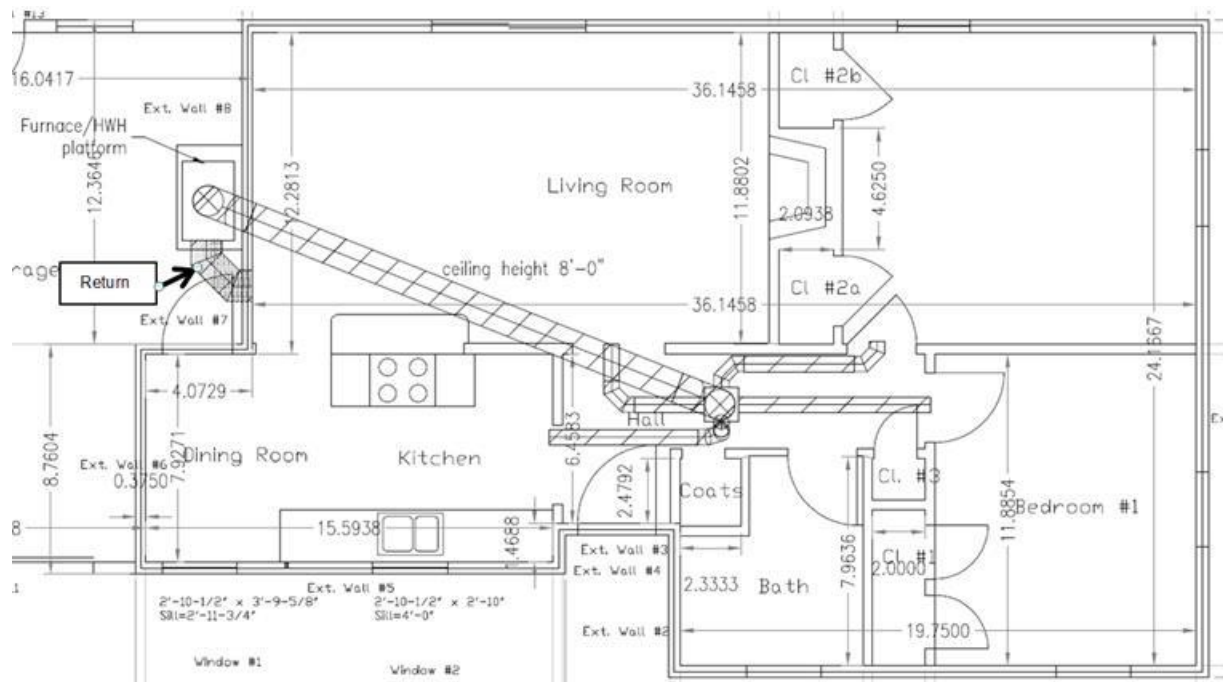
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 11: Grange – Original High Surface Area Duct Layout**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 12: Grange – Revised House Duct System**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Reference Heating, Ventilation, and Air Conditioning System

The reference HVAC system (Table 2) was used to compare the energy efficiency and peak reduction effects of the Year 1 and Year 2 retrofit measures.

**Table 2: Grange – Reference Heating, Ventilation, and Air Conditioning System**

Reference AC System	Carrier 24ANA736A0030020 with FV4VNF002 Indoor Unit 11 watts standby
Reference Duct System	Totally within conditioned space
Reference AC Rated Efficiency	15.8 SEER Locked into High Speed only (EER 11.9)
Reference AC Size	3 tons
Reference AC Airflow (measured)	357 cubic feet per minute per nominal ton
Reference External Static Pressure (measured)	0.17 inches water column total
Reference Fan Motor (measured)	1/2 HP ECM drawing 265 watts

## Baseline and Retrofit Year 1 Retrofit Packages

Table 3 and Table 4 show the baseline conditions and Retrofit Year 1 retrofit measures for the building shell and the HVAC system.

## Retrofit Year 1 Results

The results of the first retrofit year based on the 2013 Standards Sacramento/Stockton weather file are described below.

### Energy Impacts of Shell and Whole House Fan Retrofits

- Cooling season impacts: The combined air sealing (measure #1), attic insulation (#2), attic ventilation (#3), wall insulation (#4), window replacement (#6), and whole house fans (#10) reduced cooling energy use by an estimated 342 kWh or 63 percent of the reference system cooling use. See Figure 13.
- Heating season impacts: The whole house fans are not operated in the winter. In the winter, the combined air sealing (measure #1), attic insulation (#2), attic ventilation (#3), wall insulation (#4), and window replacement (#6), reduced heating energy use by an estimated 3,940 kWh (or 64 percent of the reference system electric resistance heating use. See Figure 13.



**Table 3: Grange – Building Shell, Baseline Condition and Year 1 Retrofit Measures**

Measure	Shell	Baseline Condition	Year 1 Retrofits
1	<b>Air Leakage</b>		
	Attic to House Leakage	Multiple leakage areas to the attic, including large fireplace chimney chase (see Figure 9), and between the garage and attic. (Unique kit home construction where not all interior walls are visible in the attic.)	Air sealed between conditioned space and attic and between attic and garage.
	Attic to Garage Leakage	Open	Sealed
	House Leakage	762 CFM50 (6.7 ACH50)	438 CFM50 (3.8 ACH50)
2	<b>Attic Insulation</b> (852 ft <sup>2</sup> )	Two layers of foil paper, approximately R-5	Removed and added R-49 loose-fill fiberglass
3	<b>Attic Ventilation</b>	3.5 ft <sup>2</sup> of venting (1 ft <sup>2</sup> venting to 242 ft <sup>2</sup> of ceiling area)	15.5 ft <sup>2</sup> of venting (1 ft <sup>2</sup> of venting to 55 ft <sup>2</sup> of ceiling area) to accommodate the whole house fan airflow from the house and out of the attic.
4	<b>Wall Insulation</b>	Foil paper insulation in 2 x 3 exterior walls, 960 ft <sup>2</sup> net wall area, approximately R-5	Drilled and filled to R-10 with loose-fill fiberglass
5	<b>IAQ Ventilation</b>	None	Installed ASHRAE 62.2 compliant ventilation system – Panasonic Whisper Green bath exhaust fan, 39 CFM. During its “on days,” it ran continuously and drew 5.5 watts.
6	<b>Windows</b> (78 ft <sup>2</sup> )	Aluminum, single-pane, NFRC U1.1	Vinyl, double-pane, low-E <sup>2</sup> , U 0.30, SHGC 0.25

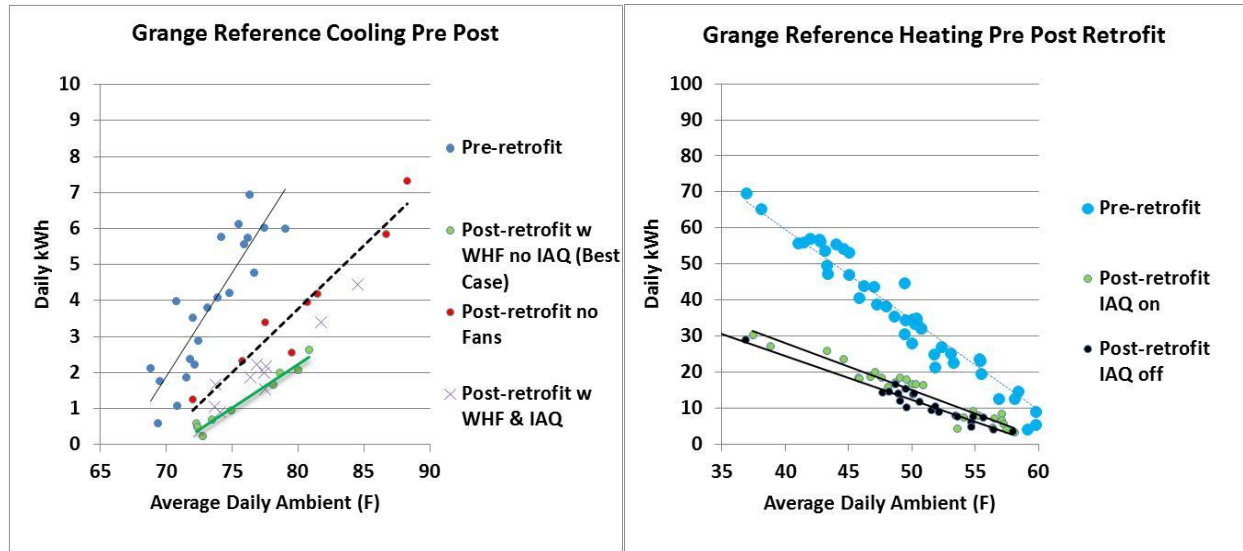
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table 4: Grange – Heating, Ventilation, and Air Conditioning System, Baseline Condition and Year 1 Retrofits**

Measure	System	Baseline Condition	Year 1 Retrofits
7	<b>Duct System</b>	Branched supply duct system. Single return from central hall to garage 38.8 ft. long, 14 in. diameter (Figure 11)	Removed old oversized duct system. Return shortened to 5 ft. Supplies replaced with single 14 in. diameter trunk duct leading to a delivery box installed in new dropped ceiling in hall. Conditioned air was run through short ducts within the dropped ceiling to each room. Except for the short return and the trunk line to the dropped ceiling, all ductwork was in conditioned space. (Figure 12)
	Duct System Leakage	8.2 percent of nominal (400 CFM per ton). 33 percent leakage using actual flow rate and pressures	Too small to measure with a Duct Blaster, 9 CFM25 or less
	Duct Surface Area (at inner liner)	352 ft <sup>2</sup> (supply 212 ft <sup>2</sup> , return 140 ft <sup>2</sup> , 41 percent of floor area, see Figure 10)	128 ft <sup>2</sup>
	Duct System Insulation	R-4.2	R-8 flex duct plus buried in new ceiling insulation (approximately R-25)
8	<b>Air Conditioning System</b>	York H2RA030S06G, Coil ICP EPD30B15B1(2.5 ton compressor)	Replaced compressor only (1 ton) Tecumseh RKA5512EXD (EER 11.09). Installed with TXV adjusted to 6° F system superheat.
	AC Rated Efficiency	10.45 SEER (9.5 EER)	No rating on new system, compressor EER 11.09
	AC Size	2.5 tons	1+ Ton
	AC Airflow	219 CFM per ton	540 CFM per ton
	Static Pressure	Total 1.13 IWC	Total 0.28 IWC
	Fan Motor	1/3 HP PSC	½ HP Concept3™ BPM
	Fan Watt Draw	361 watts	80 watts
9	<b>Heating System</b>	50,000 BTU/h 0.80 AFUE NNE050B12A1 furnace (49,200 input from meter)	Reorificed to 29,700 BTU/hr.
10	<b>Night Ventilation</b> Whole house fans use the lower outdoor temperatures to cool the house in the evening and precool the house in the morning.	None	Two whole house fans installed in ceiling. Fans moved a total of 1105 CFM of house air into the attic in cooling. They were operated on the following schedule: on from dawn to 11 a.m. and 6 p.m. to 11 p.m. as long as outside temperature was 9°F below inside temperature and inside temperature was above 68°F.* These fans have a combined power draw of 141 watts. They depressurize the building by 16.5 pascals with respect to outside and pressurize the attic by 3.4 pascals with respect to outside.
*On September 16 the allowable inside/outside temperature differential for the Whole House Fan was lowered to 3°F which allowed it to run later into the morning and earlier in the evening. After September 16 no air conditioning was used because of cooler temperatures and/or the revised WHF control. Therefore there is no definitive evaluation of how well the revised differential did in comparison to the earlier differential.			

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 13: Grange – Building Shell and Whole House Fan Effects on Reference Cooling and Heating Usage – Baseline Versus Retrofit Year 1**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

### Energy Impacts of Whole House Fans

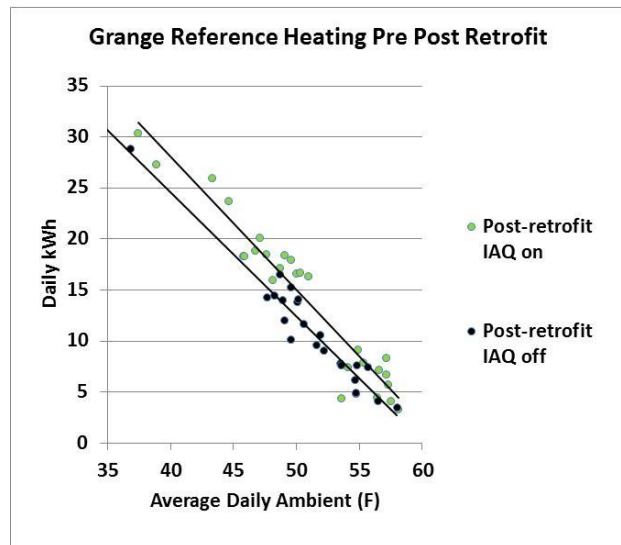
The whole house fans (measure #10) reduced the cooling load of the house. For the reference system, the reduced load decreased the gross annual energy consumption by 82 kWh or 39 percent of the Retrofit Year 1 cooling energy usage. See Figure 13 above. At the same time, the whole house fan used 16 annual kWh for a net 66 kWh energy savings. When the whole house fan load reduction is applied to the less efficient as-found house system, the net savings are 136 kWh.

### Energy Impacts of Indoor Air Quality Fan

The IAQ fan (measure #5) was alternately operated to determine the effect on the cooling and heating loads. Like the whole house fans, the IAQ fan's effect is on the cooling and heating loads. The summer cooling energy increase due to the IAQ fan is an estimated 60 kWh to the baseline house system. The net increase in usage is 84 kWh due to the fan's 5.5 Watt draw for half the year.

Similarly, the winter effect of the IAQ fan was a heating energy increase of 398 kWh as measured by the change in the reference resistance heating system. The net increase, including fan watt draw is estimated to be 422 kWh. See Figure 14.

**Figure 14: Grange – Indoor Air Quality Fan Heating Energy Use Effect**

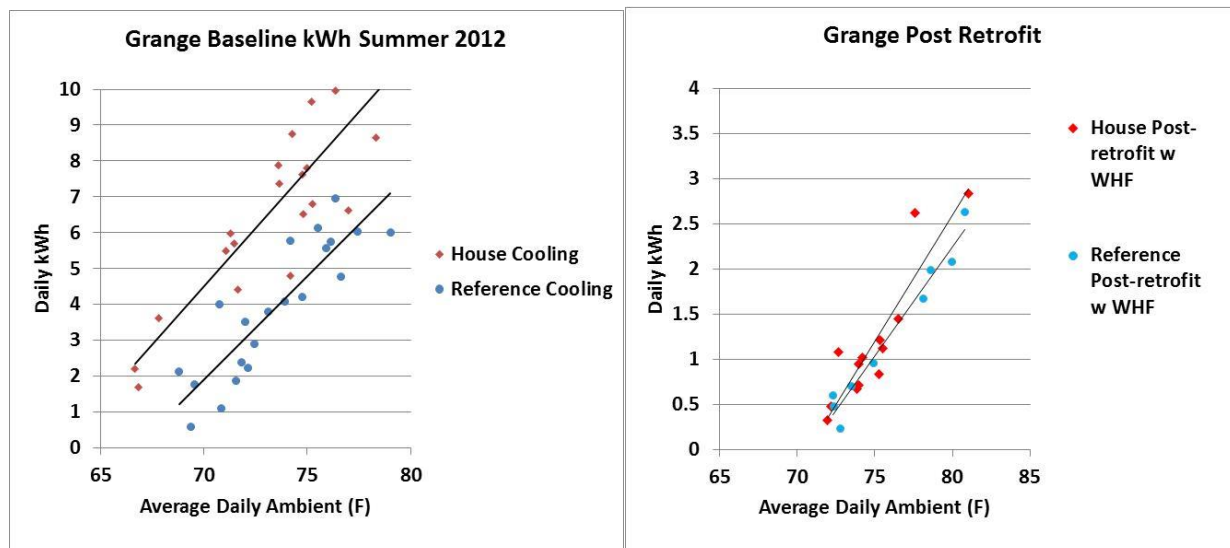


Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

### Energy Impacts of Duct and HVAC Retrofits

- Cooling season impacts: The duct rebuild (measure #7) and the AC compressor downsizing (#8) changed the house air conditioning system from 57 percent as efficient as the reference system to 84 percent as efficient as the reference system – a 33 percent cooling energy savings. See Figure 15.
- Heating season impacts: The duct rebuild and furnace derating had no discernable effect on the heating efficiency of the house system.

**Figure 15: Grange – Relative Cooling Energy Use Reference Versus House System in Baseline Year and Retrofit Year 1**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Retrofit Year 2 Measures and Results

In Year 2, a three-head ductless multi-split heat pump (also known as a variable compressor speed heat pump or VCSHP) was installed and operated in a two-way flip/flop with the reference system. The VCSHP was less efficient than the reference air conditioner in the house.

## Mayfair

### Baseline Conditions

The house on West Mayfair in Stockton, shown in Figure 16 – Figure 22, is the second oldest test home. This three-bedroom home was built in 1953 and has a floor area of 1,104 square feet. It is a simple one-story rectangular building over a crawlspace.

**Figure 16: Mayfair – Exterior**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

On the surface this house presented fewer opportunities than the other older house. It had an initial annualized<sup>5</sup> cooling energy use of 0.90 kWh/ft<sup>2</sup>, only 22 percent more than the newest home. On the other hand, it had a heating energy use of 0.29 therms per square foot, 3.6 times the heating intensity of Caleb.

The shade structure shown in Figure 17 was removed before the experiments began and the home was unoccupied when the research project team assumed the lease. The baseline conditions included steel casement and fixed single-glazed windows (Figure 18). It had a three-month old package rooftop air conditioner/furnace, shown in Figure 17. The supply and return plenums<sup>6</sup> were high in the attic and were attached to the new air conditioner/furnace. From the plenums, a brand-new but poorly installed and insulated duct system was in the attic (Figure 19). The home had minimal ceiling insulation, no insulation in the walls, crawlspace walls or raised floor.

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<sup>5</sup> Standardized to 2013 Title 24 Sacramento weather file using the methods detailed in the Methodology section.

<sup>6</sup> Plenums are air collection and distribution boxes connected to HVAC ductwork that distributes air to individual rooms in a house.



**Figure 17: Mayfair – Rear of House Faces South-Southeast**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 18: Mayfair – Steel Casement Single-Glazed Windows**



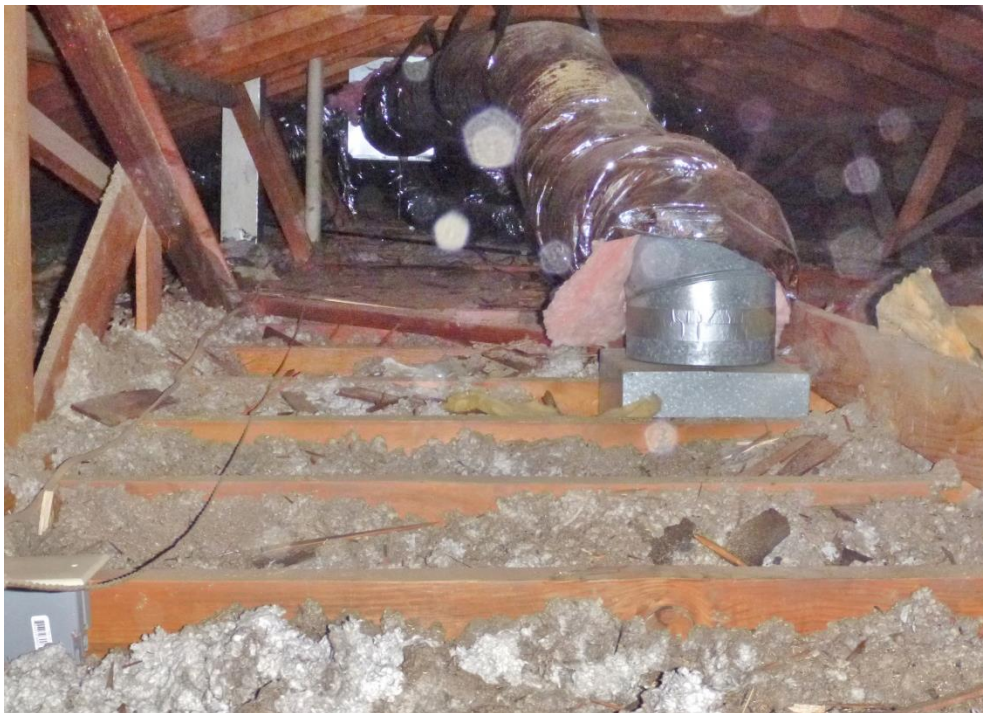
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 19: Mayfair – “Can of Worms” Duct System**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 20: Mayfair – Existing Duct System and Minimal Ceiling Insulation**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood



**Figure 21: Mayfair – Recent (Baseline) Installation SEER 13.2 Air Conditioning System**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 22: Mayfair – Unimproved and Wet Crawlspace**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood



## Reference Heating, Ventilation, and Air Conditioning System

The reference HVAC system (Table 5) was used to compare the energy efficiency and peak reduction effects of the retrofit measures.

**Table 5: Mayfair – Reference Heating, Ventilation, and Air Conditioning System**

Reference AC System	Heil NXA648GKA100 (R410A with Adjustable TXV adjusted to 6°F system superheat) Inside unit FVM4X04800A1, 10 Watts Standby
Reference Duct System	Totally within conditioned space
Reference AC Rated Efficiency	SEER 16 (EER 13)
Reference AC Size	4 tons
Reference AC Airflow (measured)	366 CFM per nominal ton
Reference External Static Pressure (measured)	0.21 inches water column total
Reference Fan Motor (measured)	3/4 HP ECM drawing 400 Watts

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Baseline and Retrofit Year 1 Packages

Table 6 and Table 7 show the baseline conditions and Retrofit Year 1 retrofit measures for the building shell and the HVAC system.

**Table 6: Mayfair – Building Shell, Baseline Condition and Year 1 Retrofits**

Measure	Shell	Baseline Condition	Year 1 Retrofits
1	<b>Crawlspace</b>	Vented and wet from faulty irrigation system	Turned off irrigation that was causing wet crawlspace and extended the downspouts
2	<b>Air Leakage</b>		
	Attic to House Leakage	Multiple leakage areas including passive vent in the kitchen, interstitial cavity at the kitchen pantry closet	Air sealing done between the attic and conditioned space reduced house air leakage by 212 CFM50*
	House Leakage	1,437 CFM50 (9.8 ACH50)	1362 CFM50 (9.3 ACH50)
3	<b>Attic Insulation</b> (1104 ft <sup>2</sup> )	R-7	Vacuumed and installed R-49 with ducts buried in the insulation. (Figure 22)
4	<b>Attic Ventilation</b>	1 to 184 (6 ft <sup>2</sup> )	1 to 55 (20 ft <sup>2</sup> , mostly low vent in front porch) (Figure 27)
5	<b>Wall Insulation</b>	No wall cavity insulation (888 ft <sup>2</sup> net area)	Drilled and filled to R-13 (Figure 28)
6	<b>IAQ Ventilation</b>	None	ASHRAE 62.2 compliant Panasonic Whisper Green bath exhaust fan, 50 CFM, drawing 3.0 watts, Flip/flop with no IAQ fan
7	<b>Windows</b> (197 ft <sup>2</sup> )	Steel casement, single pane	Vinyl frame, double pane, Low-E <sup>2</sup> (U 0.30 SHGC 0.25)
*Other changes during the retrofit had effects on the house air leakage. These effects included some changes that increased air leakage. The net air leakage result was a reduction from 1,473 CFM50 to 1,248 CFM50. "CFM50" refers to cubic feet per minute leakage at 50 Pascals pressure.			

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

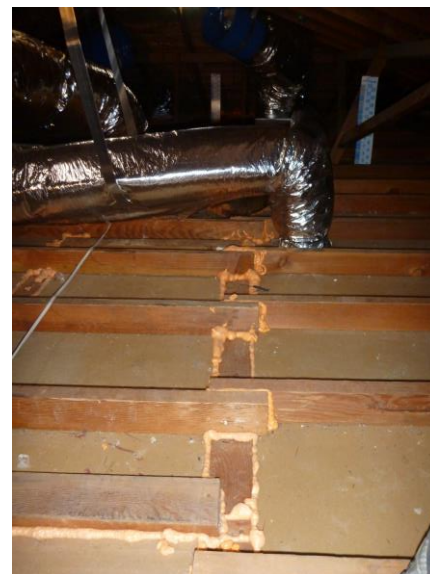
**Table 7: Mayfair – Heating, Ventilation, and Air Conditioning System, Baseline Condition and Year 1 Retrofits**

Measure	HVAC system	Baseline Condition	Year 1 Retrofits
8	<b>Duct System</b>	Restrictive duct system installed high near roof (supply and return). Included a long return containing a 180° reverse pulling from central hallway ceiling. (See Figure 24)	New double-insulated R-14 plenums dropped to the ceiling joists. Individual short supplies were run to terminals near the inside walls. A simplified return duct was run from the central hallway ceiling.
	Duct System Leakage	107 CFM25 (104 CFM25 to outside) 10.7 percent of nominal flow at 400 CFM per ton	Ducts were sealed to 27 CFM25 4.5 percent of nominal flow at 400 CFM per ton
	Duct Surface Area (at inner liner)	305 ft <sup>2</sup> (supply 192 ft <sup>2</sup> , return 113 ft <sup>2</sup> )	Return Duct 21 ft <sup>2</sup> (R-18) Return Plen. 22 ft <sup>2</sup> (R-14) Supply Duct 152 ft <sup>2</sup> (R-25) Supply Plen. 22 ft <sup>2</sup> (R-14)
	Duct System Insulation	R-6	All the new ducts (R-8) ran across the ceiling joists. This design reduced duct surface area and duct resistance. It allowed the ducts to be buried in ceiling insulation.
	Duct Supply Terminals	Stamped metal registers with internal dampers (See Figure 25)	Using the same terminal locations the ducts were simplified (including the elimination of a duct to the bathroom). The stamped supply terminals were replaced with Shoemaker CB-10 Grilles with adjustable curved blades.
9	<b>Air Conditioning System</b>	New Package Unit, D3NZ030N05606NXA	Replaced compressor only (1.5 ton) Copeland ZP16K5E-PFV-830 (EER 9.3) and adjustable TXV Danfoss TR6, R-410A, 067L5955, Johnstone B15-445 set to 6° system superheat
	AC Rated Efficiency	13.2 SEER, 11.5 EER	Not rated, delivered 19,587 Btu/hr. sensible at 90F ambient, 1,560 watts, 12.6 <u>sensible</u> EER
	AC Size	2.5 ton	1.5+ ton
	AC Airflow	362 CFM per nominal ton	612 CFM per ton
	Static Pressure	0.65 IWC	0.27 IWC
	Fan Motor	¾ HP X-13	¾ HP X-13
	Fan Watt Draw	367 watts	191 watts

Measure	HVAC system	Baseline Condition	Year 1 Retrofits
10	<b>Heating System</b>	Package Unit, D3NZ030N05606NXA 70,000 BTU/hr. 80.5 AFUE	Derated 36 percent from 65,400 to 42,100 input at meter
11	<b>Night Ventilation</b> Whole house fans use the lower outdoor temperatures to cool the house in the evening and precool the house in the morning	None	Three whole house fans were installed in ceiling. These fans moved 1520 CFM of house air into the attic in the cooling season. Operating times were from dawn to 11 p.m. as long as outside temperature was 9°F below inside temperature and inside temperature was above 68°F. These fans drew a combined 211 watts.*
<p>* On September 16, the allowable inside/outside temperature differential for the Whole House Fan was lowered to 3°F. This change allowed the WHF to run later into the morning and earlier in the evening. After September 16 air conditioning was used only on one day due to cooler temperatures and/or the revised WHF control. Therefore, there is no definitive evaluation of how well the revised differential did in comparison to the earlier differential.</p>			

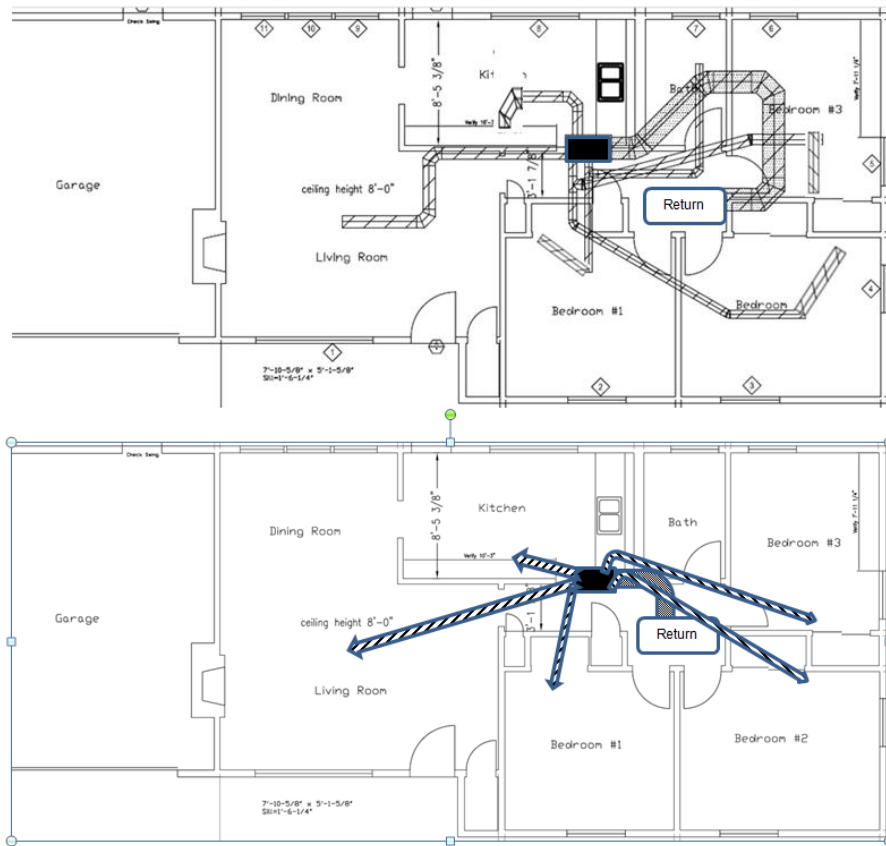
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 23: Mayfair – New Ducts and Air Sealing**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 24: Mayfair – Original and Replacement Duct Layouts**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 25: Mayfair – Original and Replacement Supply Terminals**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 26: Mayfair – Attic: R-38 Insulation, Buried Ducts and Shielded Aspirated Temperature Sensor**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 27: Mayfair – Additional Attic Ventilation**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood



**Figure 28: Mayfair – “Drill and Fill” Wall Insulation**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## **Retrofit Year 1 Results**

The results of the first retrofit year based on the Sacramento/Stockton weather file are described below.

### **Energy Impacts of Shell and Whole House Fan Retrofits**

- Cooling season impacts: The combined air sealing (measure #2), attic insulation (#3), attic ventilation (#4), wall insulation (#5), window replacement (#7), and whole house fans (#11) saved about 425 kWh or 70 percent of the reference system cooling use. See Figure 29.
- Heating season impacts: The whole house fans (measure #11) were not operated in the winter. In the winter, the air sealing (#2), attic insulation (#3), attic ventilation (#4), wall insulation (#5), and window replacement (#7) saved about 4,444 kWh or 58 percent of the reference system heating use. See Figure 29.

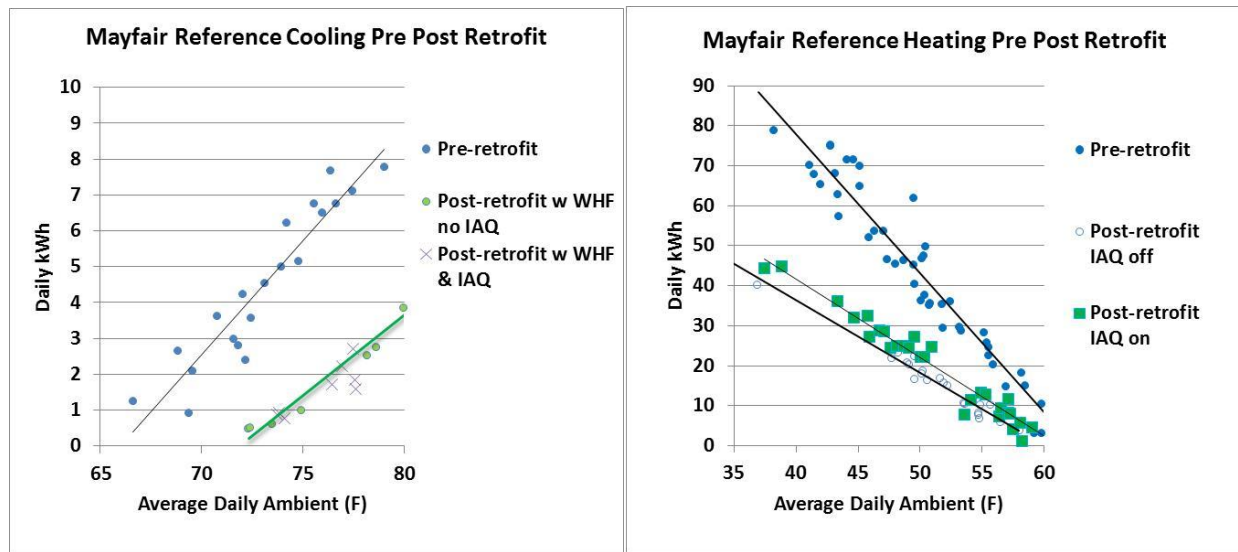
### **Energy Impacts of Whole House Fans**

The whole house fans (measure #11) reduced the cooling load of the house.<sup>7</sup> For the reference system, the reduced load decreased the estimated gross annual energy consumption by 81 kWh or 31 percent of the Retrofit Year 1 usage. At the same time the whole house fan used 13 annual kWh for a net 68 kWh energy savings. When the whole house fan load reduction is applied to the less efficient as-found house system the net savings are 121 kWh.

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<sup>7</sup> These savings are based on the whole house fan load reduction being independent of the total load on the house. As such they represent the minimum savings since higher house loads could make the whole house fans effective a larger percentage of the time.

**Figure 29: Mayfair – Building Shell and Whole House Fans Effect on Cooling and Heating Usage  
Baseline Versus Retrofit Year 1**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

### Energy Impacts of Indoor Air Quality Fan

The IAQ fan (measure #6) was alternately operated to determine the effect on the cooling and heating loads. The cooling data did not provide a consistent estimate of the load effects of the IAQ fan. Specifically, the data showed a decrease<sup>8</sup> in cooling energy consumption with the IAQ fan on in Retrofit Year 1 (with the existing crawlspace vent openings) and an increase in cooling energy consumption with the IAQ fan on in Retrofit Year 2 (with reduced crawlspace vent openings.)

The winter effect of the IAQ fan was a load increase of 576 kWh as measured by the change in the reference resistance heating system. See Figure 29.

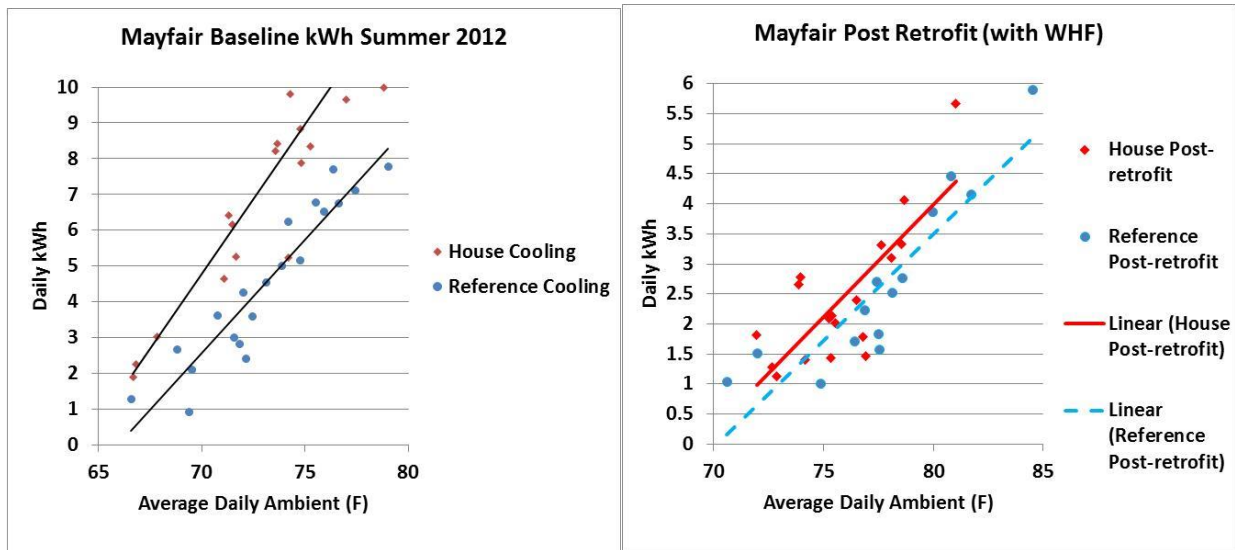
### Energy Impacts of Duct and Heating, Ventilation, and Air Conditioning Retrofits

- Cooling season impacts: The duct rebuild (measure #8) and the AC compressor downsizing (#9) changed the house air conditioning system from 61 percent as efficient as the reference system to about 91 percent as efficient as the reference system – a 33 percent cooling energy savings. See Figure 30.

The reference system continued to have an advantage over the improved house system. Figure 31 shows the hourly system kW versus the hour of the day. The point labels are the outside temperatures at that time. The house system on the left has a peak kW draw of 1.82 on a day with a peak temperature of 103°F. The reference system on the right has a peak kW of 1.32 on a day with a peak temperature of 106°F.

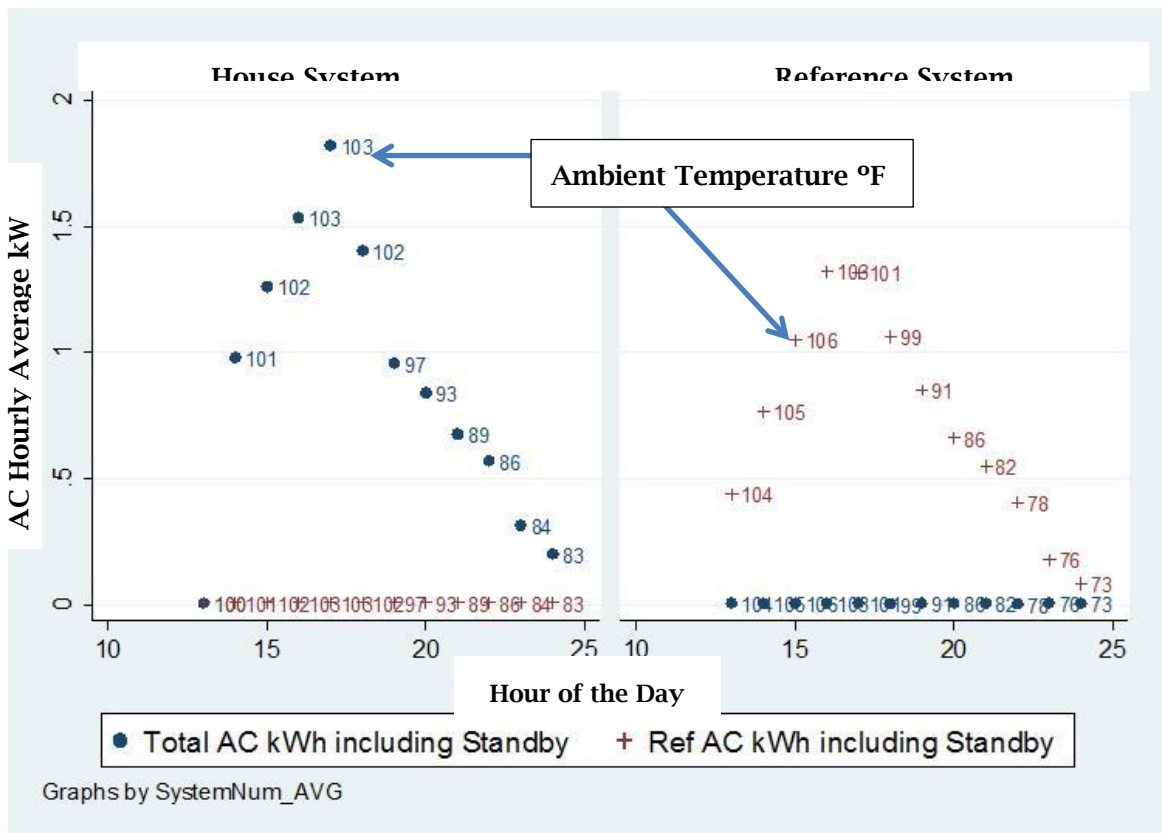
<sup>8</sup> Significant at the 0.07 level on the Reference system.

**Figure 30: Mayfair – Relative Gross Cooling Energy Use Reference Versus House System in Baseline Year and Retrofit Year 1**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 31: Mayfair – Hourly Kilowatts, Reference Versus House System in Retrofit Year 1 Versus Peak Temperatures (June 29 and July 2, 2013)**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood



- Heating season impacts: The duct rebuild (measure #8) had no discernable effect on the heating efficiency of the house heating system.

## Retrofit Year 2 Measures

The Mayfair retrofits between Retrofit Year 1 and Retrofit Year 2 are listed below. To test the ducted mini-split heat pump, the thermostat settings were changed from the Title 24 schedule to constant settings. The summer thermostat setting was 78°F and the winter setting was 68°F.

- Measure #1 – Summer. A plastic membrane was installed on crawlspace floor. Crawlspace vents were reduced to minimum code. This change reduced the house leakage from 1,362 CFM50 to 1,248 CFM50.<sup>9</sup>
- Measure #2 – Winter. The crawlspace vents were closed and the IAQ ventilation was supplied by an exhaust-only fan from the crawlspace to outside and an intentional opening from the conditioned space to the crawlspace.
- Measure #3 – Mini-split Heat Pump. A single-head ducted mini-split heat pump (also known as a variable compressor speed heat pump) was operated in a two-way flip/flop with the reference system. The variable compressor speed heat pump (VCSHP) at Mayfair was the most efficient of the three VCSHPs tested.

## Retrofit Year 2 Results

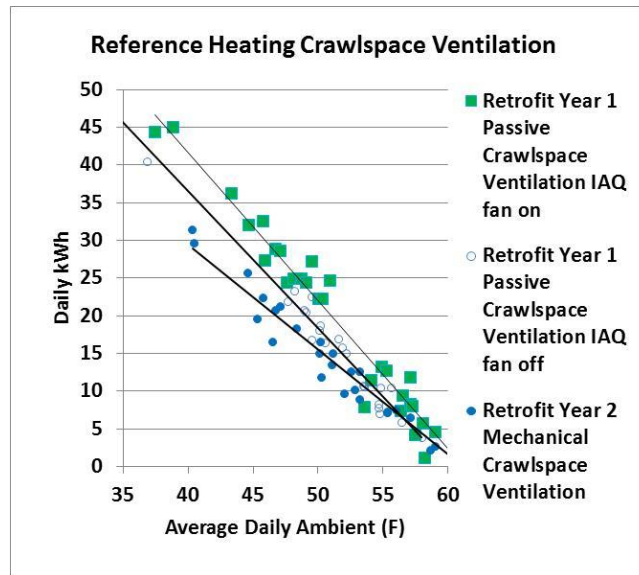
This section describes the results of the second retrofit year based on the Sacramento/Stockton weather file. The results from the Baseline and First Retrofit years are not perfectly comparable to Retrofit Year 2 because of the change from the Title 24 thermostat schedule to constant thermostat settings. The change to constant thermostat settings is likely to increase energy consumption; therefore, the estimates should be indicative of the direction and possible size of the effects.

- Measure #1 Results. The summer crawlspace vent openings reductions reduced the reference system cooling usage by about 46 kWh (25 percent of Retrofit Year 1). The sparse days with high consumption in Retrofit Year 2 along with the thermostat schedule change preclude a definitive estimate of these savings.
- Measure #2 Results. The winter blocking crawlspace vents and the new mechanical crawlspace venting accomplished three things. It reduced the house leakage, replaced the exhaust-only IAQ ventilation (and possibly reduced the IAQ ventilation rate) and eliminated a musty smell in the house. Figure 32 illustrates how that change reduced the reference system heating energy use even when compared to no IAQ ventilation. The reference System reductions are estimated to be 1222 kWh compared to reference Year 1 with exhaust IAQ and 646 kWh compared to Retrofit Year 1 with no IAQ ventilation. These are 32 percent and 20 percent reductions respectively.

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<sup>9</sup> CFM50 refers to the cubic feet per minute of air leaking during a blower-door test which depressurizes the home (to 50 pascals), making leaks easier to measure and locate.

**Figure 32: Mayfair – Reference Heating Energy Use in Passively Vented Crawlspace Versus Mechanically Vented Crawlspace**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Fidelia

### Baseline Conditions

Built in 1996, the home on Fidelia Court is the second newest test home. At 1,690 ft<sup>2</sup> it is the second largest home. The home has two stories with slab on grade construction. Three bedrooms are downstairs, with a master suite upstairs. The home's complicated footprint and numerous angles (Figure 33 – Figure 35) make insulation and other construction errors likely.

**Figure 33: Fidelia – Front Exterior**



Baseline conditions at the Fidelia house included double-glazed clear sliding windows with vinyl frames. Many windows showed considerable degradation (Figure 36). In spite of being less than 20 years old, this house had a disappointing annualized<sup>10</sup> cooling usage of 1.07 kWh/ft<sup>2</sup>, essentially equivalent to the 1948 Grange house with the foil insulation.

<sup>10</sup> Standardized to 2013 Title 24 Sacramento weather file.

**Figure 34: Fidelia – Rear Exterior**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 35: Fidelia – Can Lights, Cathedral Ceiling, Complicated Walls, Long Ducts in Attic**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 36: Fidelia – Baseline Windows**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## **Reference Heating, Ventilation, and Air Conditioning System**

The reference HVAC system (Table 8) was used to compare the energy efficiency and peak reduction effects of the retrofit measures.

**Table 8: Fidelia – Reference Heating, Ventilation, and Air Conditioning System**

Reference AC System	Heil NXA648GKA100 (R410A with Adjustable TXV adjusted to 6°F system superheat) Inside unit FVM4X04800A1, 10 Watts Standby
Reference Duct System	Totally within conditioned space
Reference AC Rated Efficiency	SEER 16 (EER 13)
Reference AC Size	4 tons
Reference AC Airflow (measured)	352 CFM per nominal ton
Reference External Static Pressure (measured)	0.21 inches water column total
Reference Fan Motor (measured)	3/4 HP ECM drawing 313 watts

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## **Baseline and Retrofit Year 1 Retrofit Packages**

Table 9 and Table 10 show the baseline conditions and Retrofit Year 1 retrofit measures for the building shell and the HVAC system.

**Table 9: Fidelia – Building Shell, Baseline Condition and Year 1 Retrofits**

Measure	Shell	Baseline Condition	Year 1 Retrofits
1	Air Leakage	Multiple ceiling levels on the top floor with air leakage pathways from below. (Figure 38)	Leakage pathways into the attic were sealed.
	Attic to House Leakage	Not known	Air sealing of top plates, electrical and plumbing
	House to Garage Leakage	Not known	Not known
	House Leakage	1,626 CFM50 (7.2 ACH50)	1,168 CFM50 (5.2 ACH50)
2	Attic Insulation (846 ft <sup>2</sup> )	R-30	Removed and added R-49
3	Attic Ventilation	2.5 ft <sup>2</sup> (1 ft <sup>2</sup> venting to 358 ceiling area (2.5 ft <sup>2</sup> ))	10.5 ft <sup>2</sup> (1 ft <sup>2</sup> venting to 85 ft <sup>2</sup> ceiling area) (10.5 ft <sup>2</sup> )
4	Wall Insulation	R-13	No change
5	Initial IAQ Ventilation	None	ASHRAE 62.2 compliant Panasonic Whisper Green bath exhaust fan, 57 CFM. During summer, drawing 4.6 watts, Flip/flop with no IAQ fan.  During the winter, the ASHRAE 62.2 compliant ventilation combined this exhaust fan and a 59 CFM supply fan drawing 62 watts. These were operated in two modes, balanced and supply only.
6	Windows (350 ft <sup>2</sup> )	Aluminum with vinyl cover strip, clear double-pane (0.65 NFRCU, 0.7 SHGC)	Vinyl frame double pane, Low-E <sup>2</sup> glass (U 0.30 SHGC 0.25)

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table 10: Fidelia – Heating, Ventilation, and Air Conditioning System, Baseline Condition and Year 1 Retrofits**

Measure	System	Baseline Condition	Year 1 Retrofits
7	Duct System	Single zone with R-4.2 ducts located between floors and in the attic with two returns, one from the upper floor through a chaseway and one on the bottom floor in the immediate proximity to the furnace/air handler, which was in the garage. The baseline duct system had three main supply branches. One ran between the floors and delivered to three of the bottom floor rooms. The second ran through an attic space to deliver to the third bedroom and bath. The third ran up a chaseway to the attic terminating in a distribution box in the attic. From the attic distribution box, long duct runs crossed the attic to supply registers on the far side of every room. (Figure 39) and Figure	The return duct from the upper floor was eliminated and the return from the lower floor enlarged. All ducts upstairs were moved inside so they are supplied through a splitter box in a dropped ceiling. The system was converted to two zones with Capacity Shift Zoning (always some flow to each zone through damper stops to eliminate full closure) The existing 1 in. pleated filter was replaced with high flow filter. The lower floor attic run was eliminated and all runs were shortened. The attic distribution box and long supply runs were eliminated and replaced by a distribution box above the upstairs closet contained within conditioned space. That gave direct access to sidewall deliveries to every upstairs room.
	Duct System Leakage	188 CFM25 13.4 percent of nominal flow at 400 CFM per ton	23 CFM25 3.8 percent of nominal flow at 400 CFM per ton
	Duct System Insulation	R-4.2	R-8.0 all inside conditioned space
8	AC System	BDP CD5BXA042000AAAA Outdoor unit BAC 561CJ042-A	Amana ASZC160241AE Air Handler AVPTC313714AA Crankcase Heater 40 watts switches on when dropping below 65° F and off when it rises above 88°F
	AC Rated Efficiency	10 SEER (9 EER)	The replacement heat pump was a two speed unit SEER 16.0 locked on low speed. A low speed 12.65 EER.
	AC Size	3.5 tons	1.4 ton low speed heat pump
	AC Airflow	390 CFM per ton	542 CFM per ton
	Static Pressure	Not Measured	0.31 IWC, Total External
	Fan Motor	PSC	¾ HP ECM
	Fan Watt Draw	554 watts	78 watts
9	Heating System	88,000 Btu/h 0.80 AFUE Bryant Furnace 383KAV048091 Standby watts for furnace: 6 watts	Amana ASZC160241AE heat pump detailed above (Figure 37). Standby watts for air handler and zone controls: 15 watts.



Measure	System	Baseline Condition	Year 1 Retrofits
			The capacity was 16,600 Btu/h at 47 ambient. The COP rating at that temperature is 3.67
10	Night Ventilation	None	Three whole house fans were installed in the ceiling. These fans moved 1,593 CFM of house air into the attic in cooling. Operating schedule: on from dawn to 11 p.m. as long as outside temperature is was 9°F below inside temperature and inside temperature is was above 70°F. These fans draw a combined 219 watts. They depressurize the building by 13.1 pascals with respect to outside and pressurize the attic by 3.4 pascals with respect to outside.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 37: Fidelia – New 1.5 Ton Heat Pump (locked on low speed)**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 38: Fidelia – Multiple Ceiling Levels and Upper Floor Return**



Multiple Ceiling Levels  
and Leaks from  
Interior Walls to Attic

Original Ducted  
Upstairs Return into  
Chaseway to Lower  
Level

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

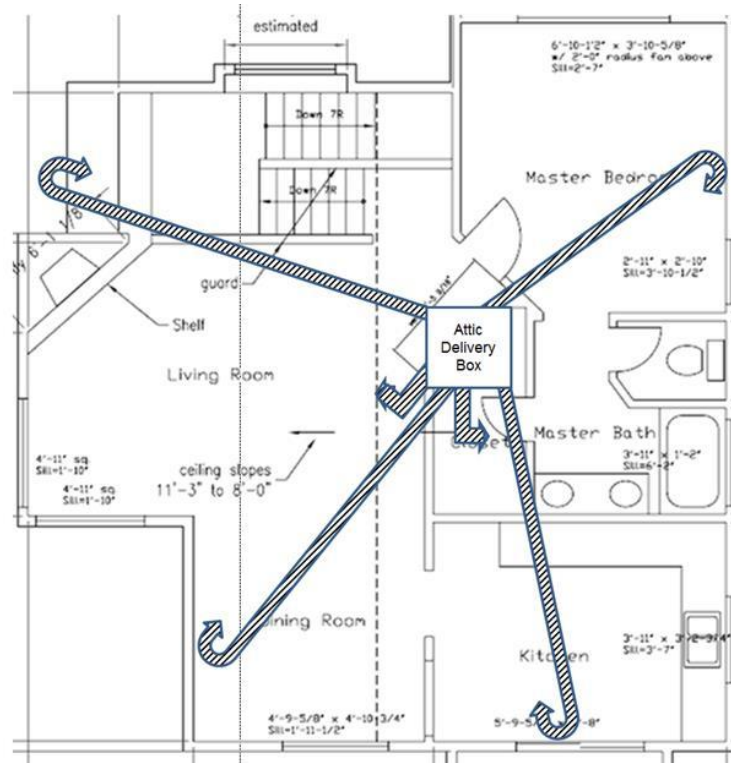
**Figure 39: Fidelia – Attic As-found Heating, Ventilation, and Air Conditioning Delivery Box and Long Attic Duct Runs**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

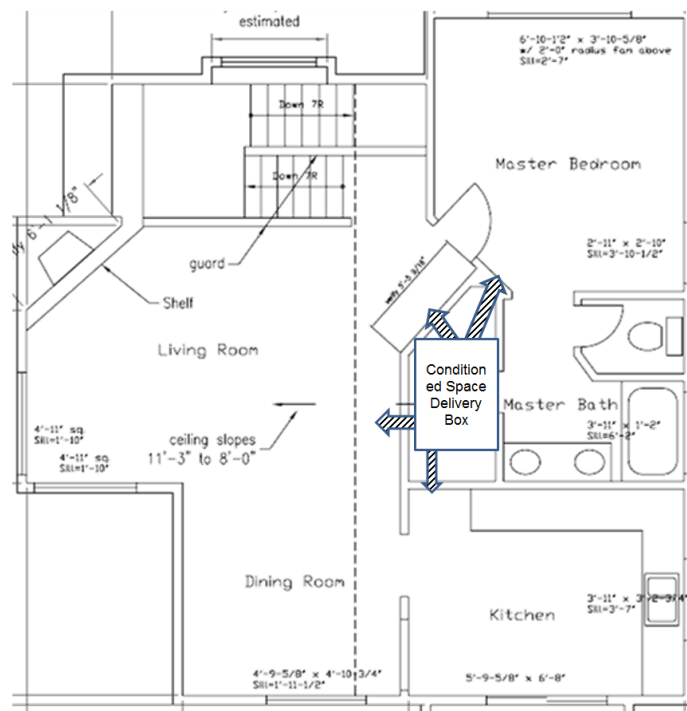


**Figure 40: Fidelia – As-found Top Story Supply Duct System Layout**



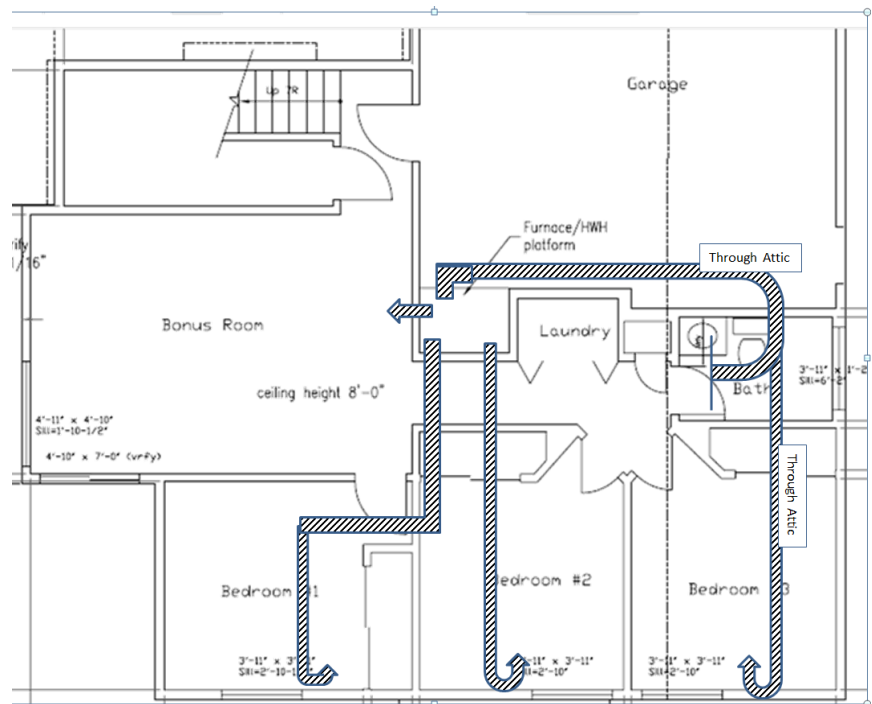
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 41: Fidelia – Retrofit Top Story Supply Duct System Layout**



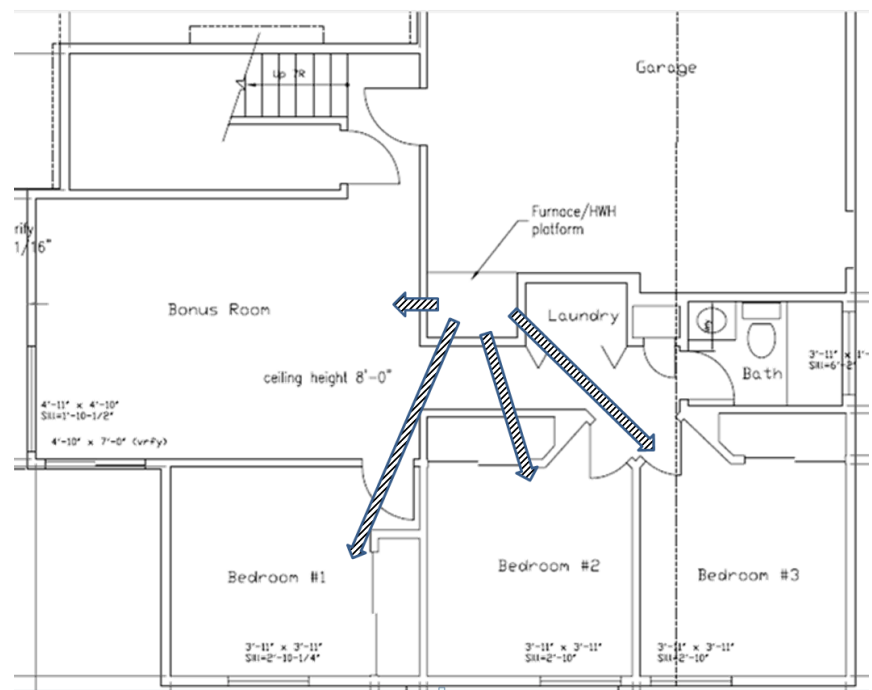
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 42: Fidelia – As-found Bottom Story Supply Duct Layout**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 43: Fidelia – Retrofit Bottom Story Supply Duct Layout**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

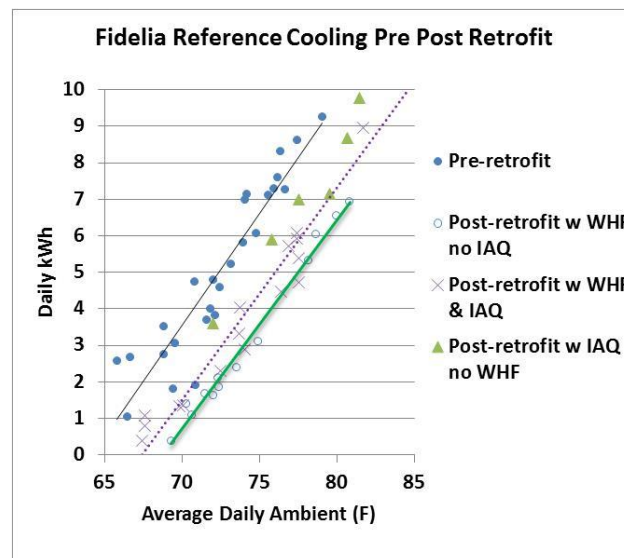
## Retrofit Year 1 Results

This section describes the results of the first retrofit year based on the Sacramento/Stockton weather file.

### Energy Impacts of Shell Retrofits

The combined air sealing (measure #1), reinsulating the attic to R-49 (#2), passive ventilation (#3) and window replacement (#6) saved an estimated 220 kWh or 30 percent of the reference system cooling use (Figure 51). These measures also achieved a 23 percent heating savings with the reference system.

**Figure 44: Fidelia – Shell Improvement Cooling Energy Savings**

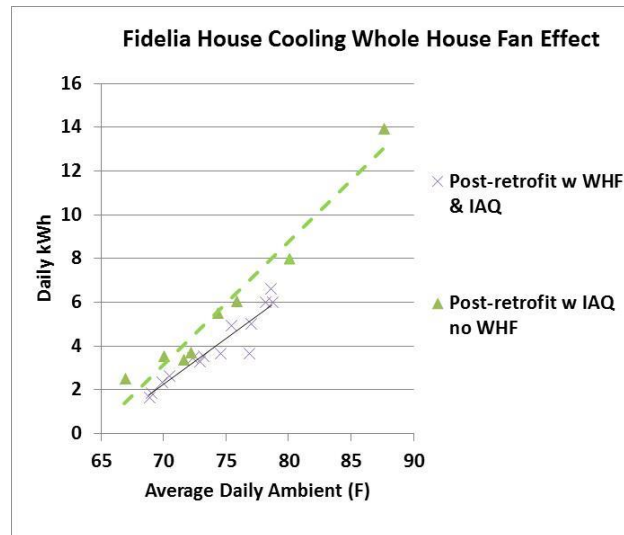


Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

### Energy Impacts of Whole House Fan Retrofit

The whole house fans (measure #10) reduced the cooling load. For the reference system, the reduced load decreased the estimated gross annual energy consumption by 93 kWh or 19 percent of the Retrofit Year 1 usage. At the same time the whole house fan used 22 annual kWh for a net 71 kWh energy savings. When the whole house fan load reduction is applied to the less efficient as-found house system, the net savings is 212 kWh (Figure 45). This experiment was expanded in the second retrofit year.

**Figure 45: Fidelia – Whole House Fan Cooling Energy Savings Post Retrofit Year 1**



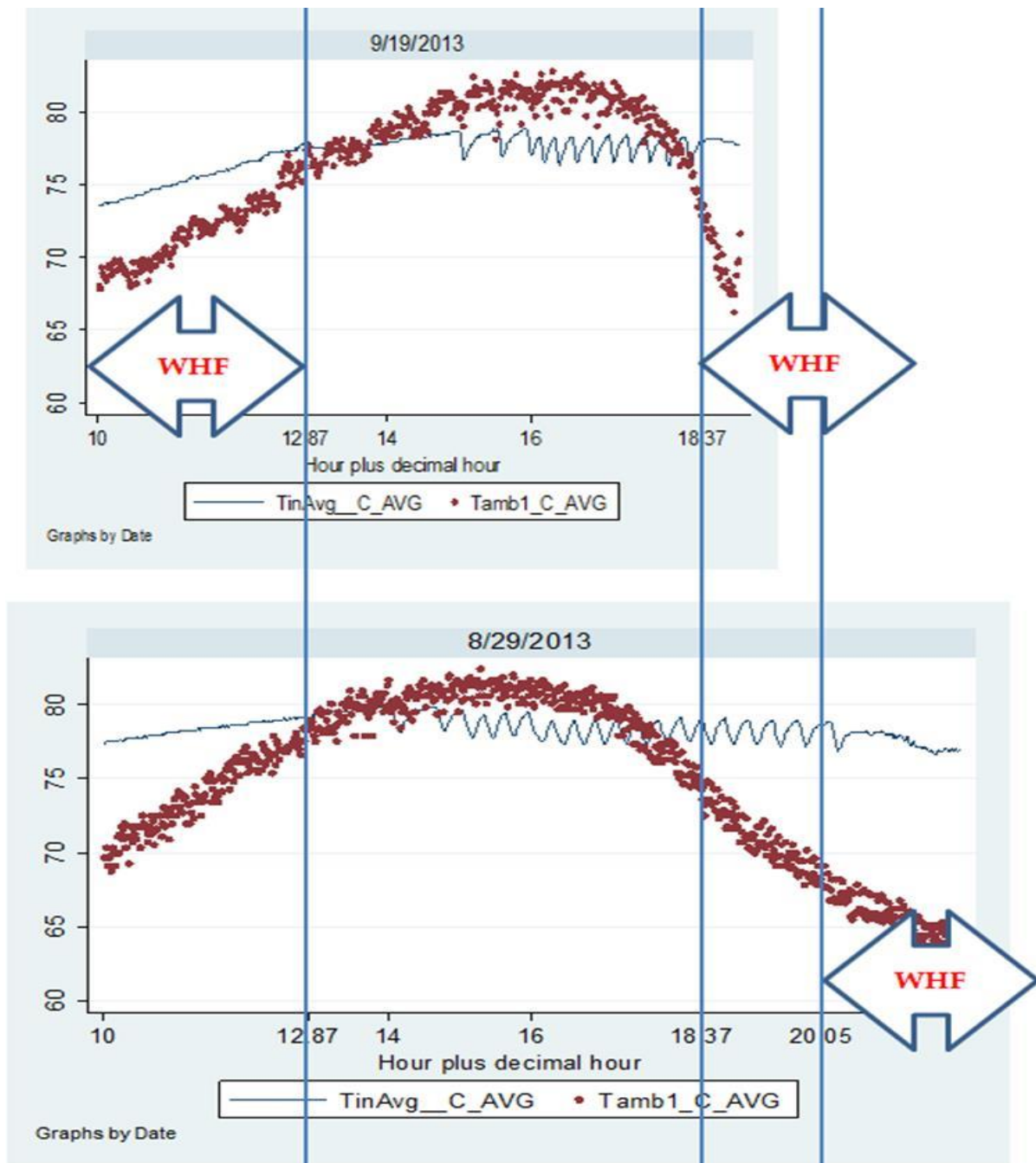
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

On September 16, the allowable inside/outside temperature differential for the whole house fan was lowered to 3°F. This change allowed the whole house fan to run later into the morning and earlier in the evening. Figure 46 shows two similar days, August 29 before the temperature on differential was lowered and September 19 after the temperature on differential was lowered. On August 29 the whole house fan did not come on in the morning and only came on after 8:00 p.m. On September 16 the whole house fan ran in the morning until well after noon. That evening the whole house fan came on at 6:20 p.m. The air conditioner ran three times longer on August 29 as it did on September 16. These are only two days so a definitive result cannot be stated.

### Energy Impacts of Duct and HVAC Retrofits

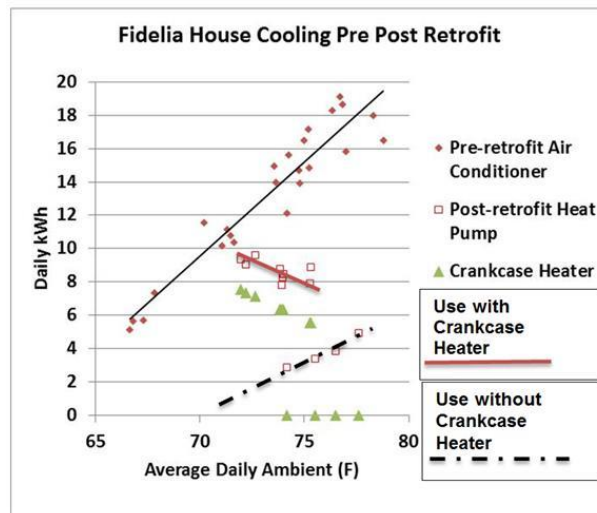
Moving the duct system for the top floor out of the attic (measure #7) and installing the 1.5 ton heat pump in place of the existing air conditioner (measure #8) changed the house system from 60 percent less efficient than the reference system to 14 percent more efficient – a 65 percent cooling energy savings in the absence of the zoning control and crankcase heater losses. However, the crankcase heater added a seasonal 108 kWh (Figure 47). This excessive crankcase heater energy consumption was addressed in Year 2 retrofits.

Figure 46: Fidelia – Effect of Whole House Fan-on Differential Settings



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 47: Fidelia – Pre and Post-retrofit Year 1 Cooling Energy Use Showing Excessive Crankcase Heater Involvement**



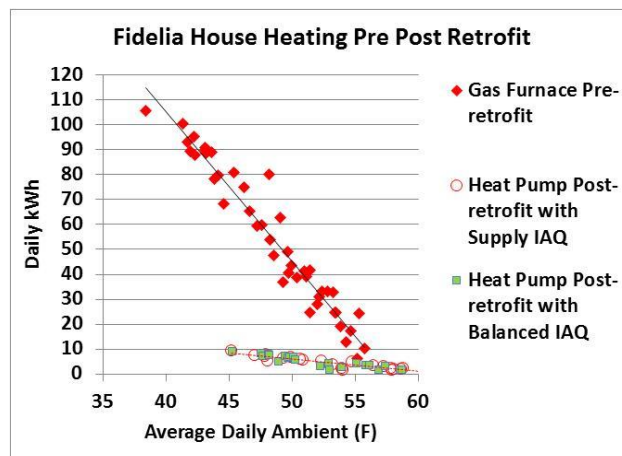
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

Duct system modifications (measure #7), zoning with adequate airflow (#8) and the heat pump replacing the furnace (#9) made very large changes in the site heating energy usage. This was expected since the heat pump alone would be expected to reduce the site energy usage by 78 percent. The expected site savings is determined by the following equation:

$$\text{Percentage Savings} = (COP - AFUE)/COP$$

In the absence of the crankcase heater that was on almost continuously in the winter, these modifications saved 86 percent of the site heating energy (Figure 48).

**Figure 48: Fidelia – Pre and Post-retrofit Year 1 Site Energy Heating Use Showing the Effects of All Measures**

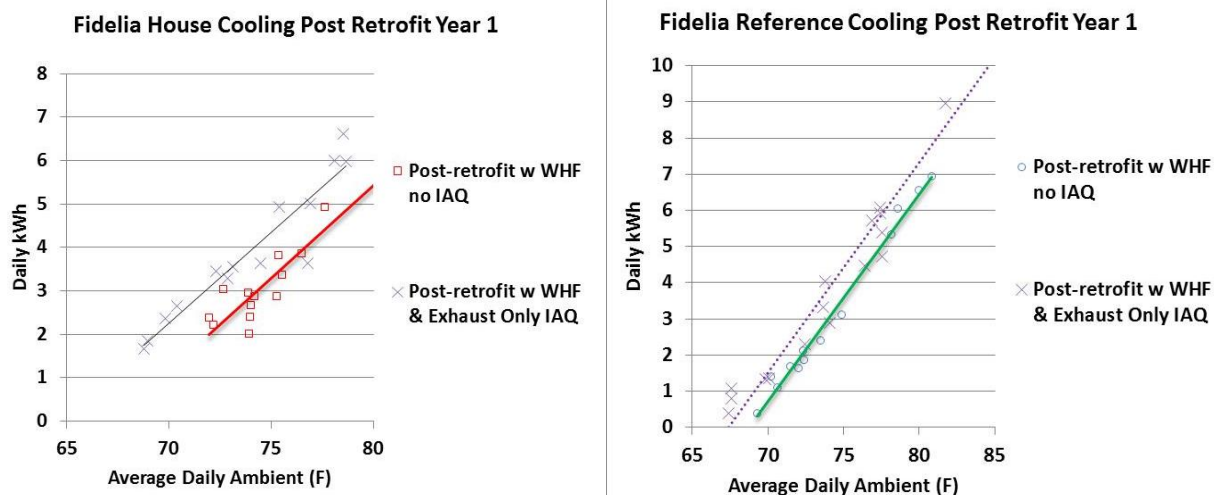


Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Energy Impacts of Indoor Air Quality Fan Retrofit

In the summer, the exhaust-only American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.2 compliant ventilation (measure #5) increased the cooling energy use by an estimated 63 kWh for the reference system (16 percent) and 72 kWh for the house system (21 percent). See Figure 49.

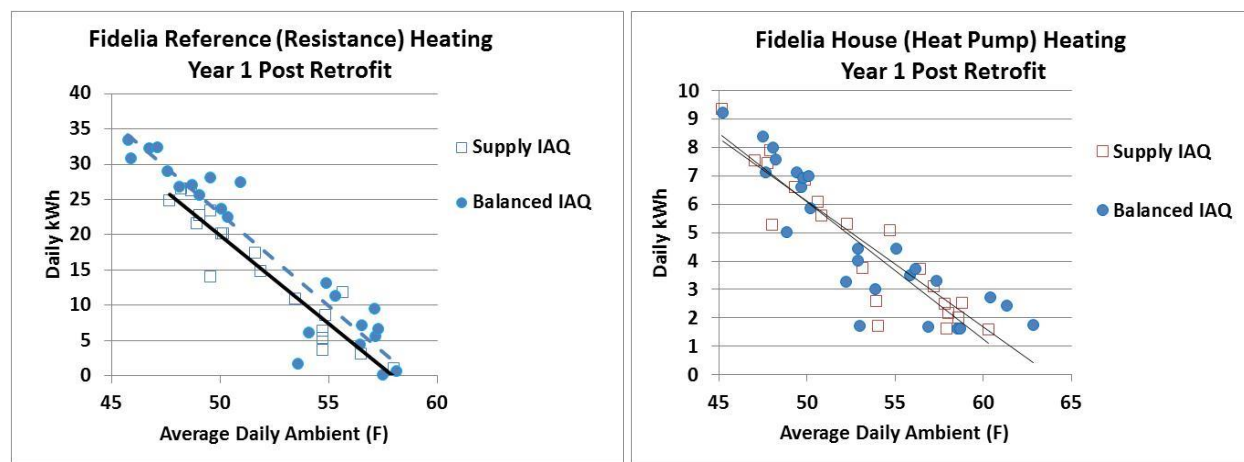
**Figure 49: Fidelia – Post-retrofit Year 1 Cooling Energy Use Showing the Effect of Exhaust-Only Ventilation**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

In the winter, the comparison between the balanced ventilation system and the supply-only system (measure #5) showed mixed results (Figure 50). The balanced system increased the measured heating energy consumption for the reference system by 10 percent over the supply-only ventilation. However, the difference between the balanced system and the supply-only system was not discernable in the house system heat pump data.

**Figure 50: Fidelia – Post-retrofit Year 1 Heating Energy Use Comparing Supply-Only and Balanced Ventilation**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Retrofit Year 2 Measures

The Fidelia retrofits between Retrofit Year 1 and Retrofit Year 2 were:

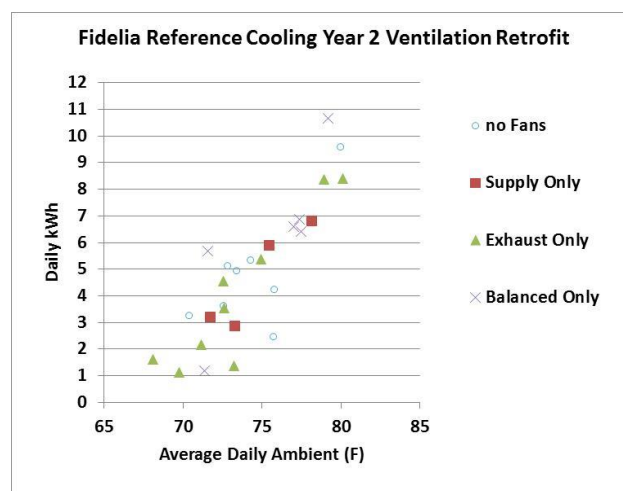
- **Summer Ventilation:** The ventilation supply and ventilation exhaust fans were cycled through four modes: Supply-only, Exhaust-only, Balanced and No IAQ ventilation. Only the reference air conditioner was run during the summer in an attempt to capture consistent data on the four ventilation modes.
- **Winter Ventilation:** The ventilation supply and ventilation exhaust fans were alternated: Supply only or Exhaust only.
- **Whole House Fan Control:** Temperature set points remained the same (outside 9°F or more below inside temperature, minimum inside temperature 70°F). The control would now allow whole house fan operation any time of the day.
- **Heat Pump Controls:** A crankcase heater lockout was added. This control did not allow crankcase heat at temperatures above 40°F. A defrost lockout was added that did not allow defrosting unless the pressure drop across the outside coil showed considerable frost buildup.

## Retrofit Year 2 Results

This section describes the results of the second retrofit year based on the Sacramento/Stockton weather file.

- **Measure 1 – Summer Ventilation.** The summer four-way rotation did not provide sufficient data to discern the difference between the four ventilation modes (Figure 51).

**Figure 51: Fidelia – Ventilation Data Four-Way Test – Insufficient Data**

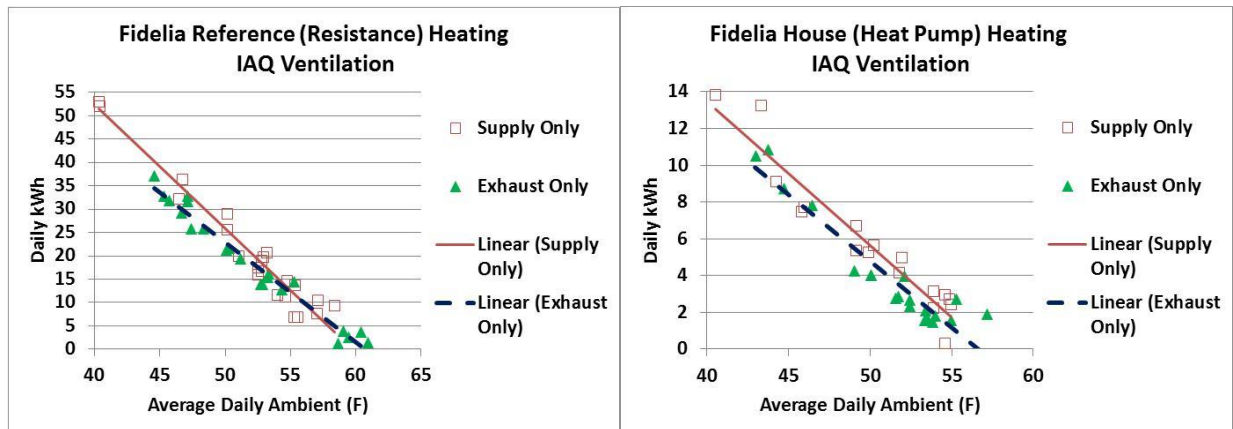


Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

- **Measure 2 – Winter Ventilation.** Supply-only ventilation showed 541 kWh (9 percent) higher heating load and 160 kWh (16 percent) higher heat pump use when compared to the Exhaust-only ventilation strategy. See Figure 52.



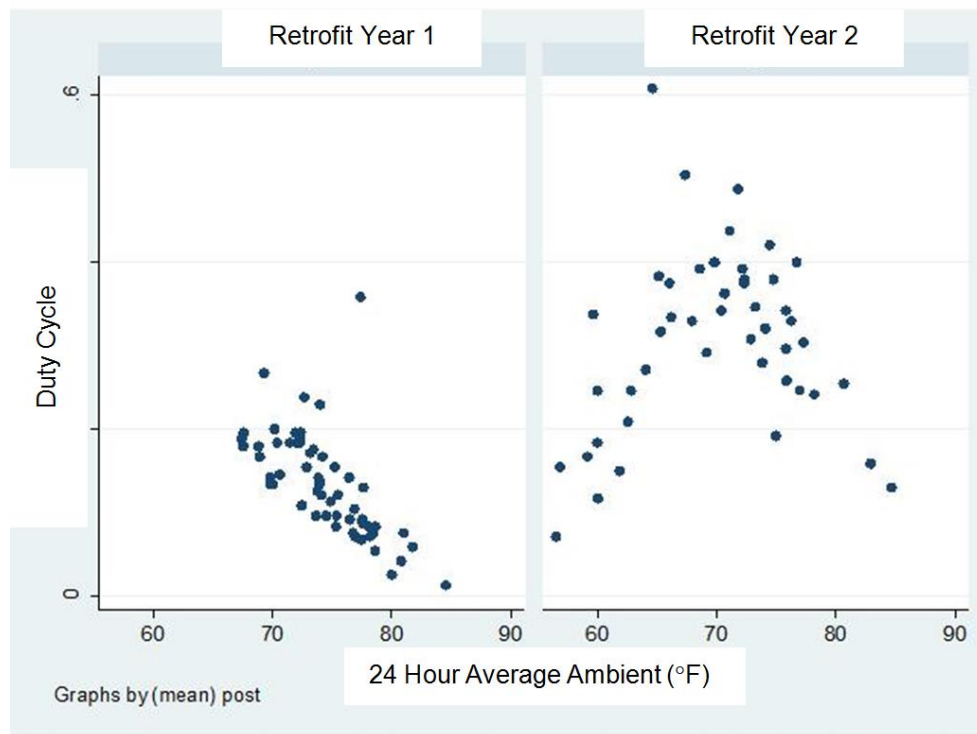
**Figure 52: Fidelia – Supply-Only Versus Exhaust-Only Ventilation in Heating**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

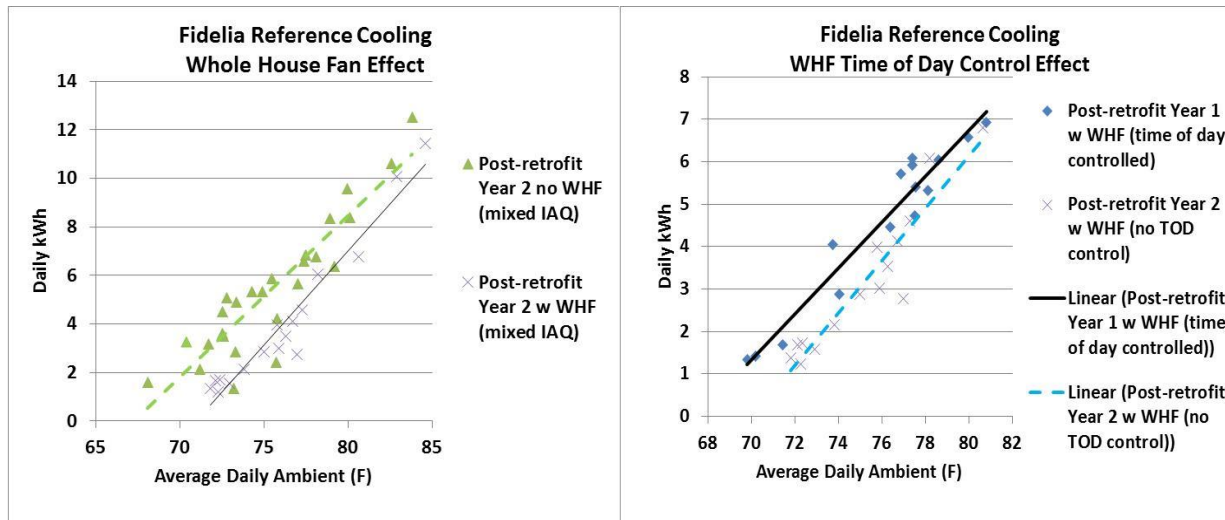
- Measure 3 – Whole House Fan Control. The whole house fan operated without time of day constraints. This change made a substantial difference in the reference system whole house fan cooling, reducing the gross reference system cooling usage by 319 kWh and the net reference cooling use by 269 kWh (18 percent). See Figure 53 and Figure 54.

**Figure 53: Fidelia – Extended Whole House Fan Duty Cycle, Retrofit Year 1 Versus Year 2**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

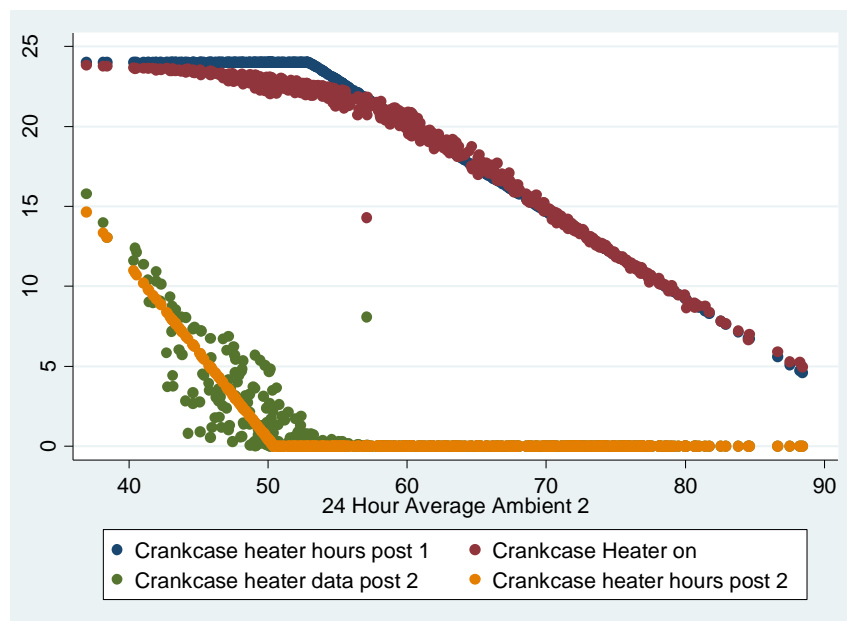
**Figure 54: Fidelia – Extended Whole House Fan Duty Cycle, Cooling Energy Savings**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

- Measure 4 – Crankcase Heater and Defrost Control. The crankcase heater controller worked as expected, eliminating crankcase heating above 40°F (note that the figure shows the daily average outdoor temperature, while the crankcase heater temperature control is instantaneous). No defrost cycles were identified in the Retrofit Year 2 data. The crankcase control saved 108 kWh in the summer and 153 kWh in the winter. Figure 55 shows a splined fit to the crankcase heater daily run hours for Retrofit Year 1 (labeled “post 1” in the figure) and Retrofit Year 2 (labeled “post 2”).

**Figure 55: Fidelia – Crankcase Heater Daily Run Hours Retrofit Year 1 (as Manufactured) Versus Retrofit Year 2 (Added Temperature Control)**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

# Caleb

## Baseline Conditions

Built in 2005, the four bedroom, 2,076 ft<sup>2</sup> house on Caleb Circle is the newest and largest of the test houses (Figure 56). It is a two-story rectangular home with a partial tuck-under garage (Figure 57).

**Figure 56: Caleb – Exterior Front and Side View**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

This house has low-E double-pane windows. The HVAC equipment and ducts are in the attic under a tile roof (Figure 58 and Figure 59). This house is similar to the 2008 Title 24 code and provides the greatest challenge to procuring retrofit savings. The initial annualized<sup>11</sup> cooling use for this house was the lowest of the four houses at 0.74 kWh/ft<sup>2</sup>.

**Figure 57: Caleb – Exterior Rear**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

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<sup>11</sup> Standardized to 2013 Title 24 Sacramento weather file.

**Figure 58: Caleb – Heating, Ventilation, and Air Conditioning and Ducts in Attic under Tile Roof**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 59: Caleb – Attic Insulation and Ducts above Insulation Strapped to Roof**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Reference Heating, Ventilation, and Air Conditioning System

The reference HVAC system (Table 11) was used to by which to compare the energy efficiency and peak reduction effects of the retrofit measures.

**Table 11: Caleb – Reference Heating, Ventilation, and Air Conditioning System**

Reference AC System	Carrier 24ANA736A0030020 with FV4VNF002 Indoor Unit
Reference Duct System	Totally within conditioned space
Reference AC Rated Efficiency	15.8 SEER Locked into High Speed only (EER 11.9)
Reference AC Size	3 tons
Reference AC Airflow (measured)	370 CFM per nominal ton
Reference External Static Pressure (measured)	0.30 inches water column total
Reference Fan Motor (measured)	1/2 HP ECM drawing 386 watts

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Baseline and Retrofit Year 1 Retrofit Packages

Table 12 and Table 13 show the baseline conditions and Retrofit Year 1 retrofit measures for the building shell and the HVAC system. Some of these retrofit measures are shown in Figure 60 and Figure 61.

**Table 12: Caleb – Building Shell, Baseline Condition and Year 1 Retrofits**

Measure	Shell	Baseline Condition	Year 1 Retrofits
1	Roof Deck Insulation	None	Removed existing roof tile and replaced with PolyFoam (3M) PolySet spray foam system under roofing tiles (Figure 60)
2	Air Leakage		
	House Leakage	1494 CFM50 (5.0 ACH50)	1615 CFM 50 (5.4 ACH50)
3	Attic Insulation	R-30	No change
4	Attic Ventilation	7.1 ft <sup>2</sup> (1 ft <sup>2</sup> venting to 154 ft <sup>2</sup> ceiling area)	16.7 ft <sup>2</sup> (1 ft <sup>2</sup> venting to 66 ft <sup>2</sup> ceiling area) to accommodate the whole house fan airflow from the house and out of the attic.
5	Wall Insulation	R-17	No change
6	IAQ Ventilation	None	ASHRAE 62.2 compliant ventilation (Panasonic Whisper Green Bath Exhaust Fan, 64 CFM) was added and operated on a flip/flop schedule. During its “on” days it ran continuously and drew 12.1 watts.
7	Windows	Double-pane, low-E (0.3 SHGC 0.35 NFRC U)	No change

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table 13: Caleb – Heating, Ventilation, and Air Conditioning System, Baseline Condition and Year 1 Retrofits**

Measure	HVAC system	Baseline Condition	Year 1 Retrofits
8	Duct System	Two-zone dampered duct system (upstairs/downstairs) with no bypass	Installed “Capacity Shift Zoning” (always some flow to each zone; see Figure 62). Removed one small 4 in. supply duct, adjusted damper stops to eliminate full closure, moved one supply from zone control to constant. Replaced 1 in. pleated filter with high flow filter. Total cooling air flow with upstairs only calling is 1,107 CFM – 857 CFM to the upstairs and 250 CFM (23 percent) to the lower floor when the upstairs was calling for conditioning.
	Duct System Leakage	213 CFM25 (13.3 percent of nominal 1600 CFM)	Minor duct repairs reduced leakage to 170 CFM25 (17 percent of nominal 1000 CFM)
	Duct System Insulation	R-6	No change
	Duct Surface Area (at inner liner)	Unknown	No change
9	AC System	Carrier 38 CKC048370 with All Style ASFM4842	Maratherm (ICP) Model R2A330GKR2, 2.5 tons, R-22 dry-ship. Replaced outside unit only; baseline indoor air conditioner coil and furnace were retained. This downsized the compressor relative to the evaporator coil. The original fixed refrigerant metering device was replaced with an adjustable TXV. The system superheat was adjusted to 6°F.
	AC Rated Efficiency	10 SEER (9.25 EER)	13.0 SEER (11 EER)
	AC Size	4 tons	2.5 tons (replaced outside unit only)
	AC Airflow	215 CFM per ton (upstairs only calling for cooling)	The combination of the duct changes (#8), the downsizing and the motor replacement increased the airflow to 443 CFM per ton (upstairs only calling for cooling)
	Static Pressure	0.98 IWC total (upstairs only calling for cooling)	0.41 IWC total (upstairs only calling for cooling)
	Fan Motor	½ HP permanent split capacitor (PSC) FLA 7.9	Concept3™ brushless permanent magnet (BPM) with proportional fan time delay on low speed (Western



Measure	HVAC system	Baseline Condition	Year 1 Retrofits
			Cooling Control™). This particular motor has a climate sensitive evaporator fan delay.
	Fan Watt Draw	584 watts	293 watts
10	Heating System	90,000 BTU/h 0.80 AFUE Carrier 58STX090-16 furnace	No change
11	Night Ventilation	None	Four whole house fans installed in ceiling. These fans move house air into the attic. Total fan flow was 2,075 CFM. The fans operated from dawn to 11 p.m. It operated as long as outside temperature was 4.5°F or more below inside temperature and the average inside temperature was above 70°F. These fans depressurized the house by 20.4 pascals (0.082 inches of water column) with respect to outside and pressurized the attic by 1.6 pascals with respect to outside. The fans consumed 275 watts when running. Outside air entered the house through a filtered, powered damper in the house sidewall.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 60: Caleb – Roof Tile Adhesive**



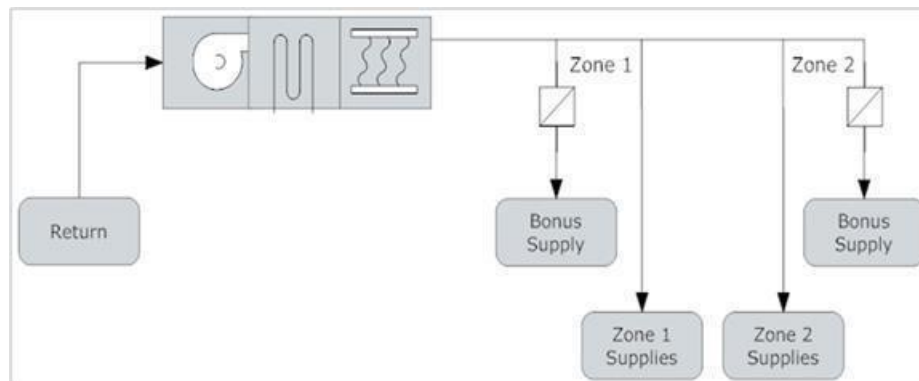
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 61: Caleb – Whole House Fan in Attic and Sidewall Outside-Air Automatic Damper**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 62: Example of Capacity Shift Zoning**



With Capacity Shift Zoning, the zoned system never attempts to limit the delivery of capacity to only one zone, but rather prioritizes (sends more of) the air flow and capacity to the zone that is showing an increased heating or cooling load. This figure shows Capacity Shift Zoning with the main supply terminals always obtaining flow and one or more bonus supply terminals on each zone for shifting capacity to follow the load.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Retrofit Year 1 Results

This section describes the results of the first-year retrofits with savings estimates based on the 2013 Sacramento/Stockton weather file.

### Energy Impacts of Shell Retrofits

Insulating adhesive under roof tiles (measure #1) provided inconclusive results in the cooling mode in 2013 (Retrofit Year 1) potentially due to insufficient data. The experiment was

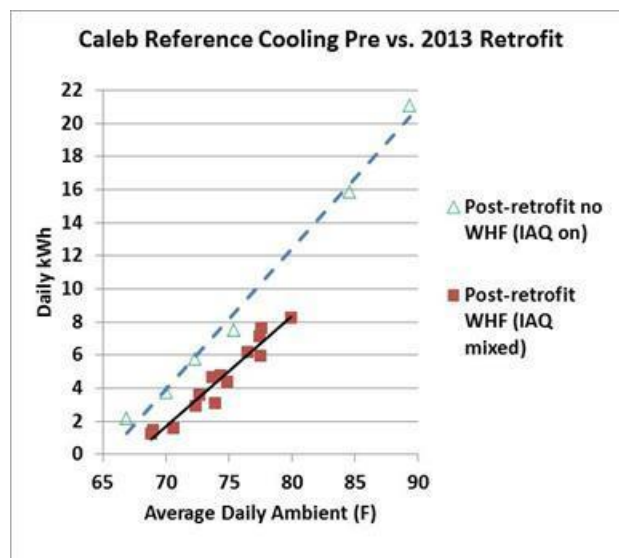


continued into Retrofit Year 2, and results are presented later. The data suggest that the heating energy use may have increased. Changes in the insulation on this house were not likely to be cost effective, so the roof insulation package was the only one tested.

### Energy Impacts of Whole House Fan Retrofit

Whole house fans (measure #11) provided noticeable improvement in cooling energy efficiency. For the reference system, the estimated savings was 357 kWh or 40 percent of the annual cooling use. See Figure 63. These data are compromised by the malfunction of a third cooling system in this house during Retrofit Year 1. The experiment was continued into Retrofit Year 2.

**Figure 63: Caleb – Energy Savings from Whole House Fans**

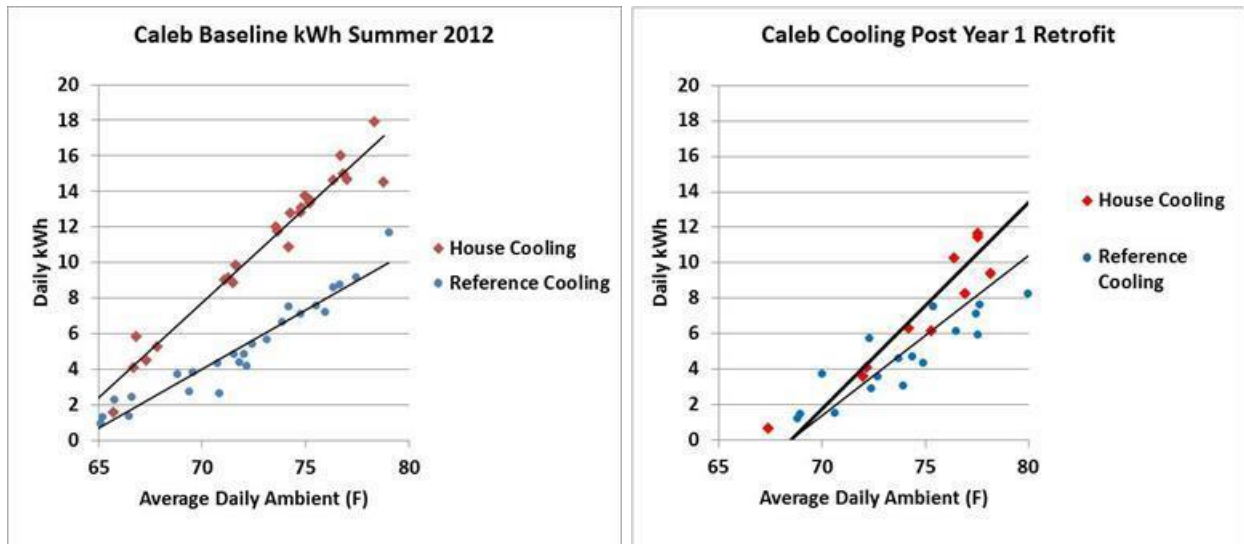


Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

### Energy Impacts of Duct and Air Conditioning System Retrofits

Duct system modifications (measure #8), outdoor unit replacement and fan motor replacement (#9) provided a large improvement in cooling energy efficiency. The baseline house system used 190 percent of the cooling energy of the reference system. The Year 1 retrofits reduced the house system cooling usage to about 120 percent of the reference system. See Figure 64 comparing the baseline plots on the left against the Year 1 retrofits on the right; the house system and reference system have a much more similar performance with the retrofit.

**Figure 64: Caleb – Improvement in House Air Conditioning System Efficiency between Baseline and Retrofit Year 1**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

### Energy Impacts of Indoor Air Quality Fan

The IAQ exhaust-only ventilation (measure #6) increased the cooling energy consumption of the house system in the cooling mode by 12 percent to 14 percent. In the heating mode, it increased the total heating energy consumption of the house system by an estimated 16 percent to 19 percent (1,130 kWh). The IAQ experiment was terminated in Retrofit Year 2.

### Retrofit Year 2 Measures

The Caleb retrofit measures tested in the Retrofit Year 2 were:

- The roof deck insulation under the roof tiles was still present as described above in Retrofit Year 1.
- The whole house fans were still present and operated under the same control scenario described in Retrofit Year 1.
- The heating and cooling duct system remained modified as described in Retrofit Year 1. However, the air conditioner underwent additional modifications: the original 4 ton, 10 SEER outdoor AC unit was reinstalled and operated with the adjustable TXV installed in Retrofit Year 1. The BPM evaporator fan motor was replaced with a standard PSC motor. The reinstallation of the 4 ton condensing unit and the installation of the standard PSC motor decreased the airflow from 443 CFM per ton to 276 CFM per ton with upstairs calling for cooling. The fan motor watt draw increased from 293 watts with the BPM motor to 660 watts with the PSC motor.

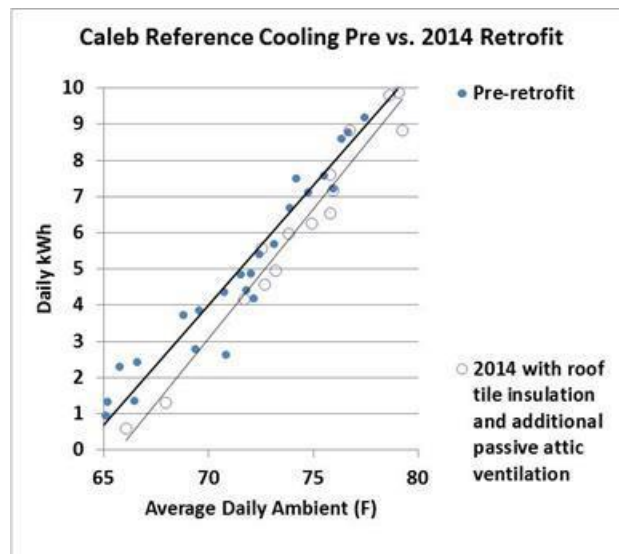
- The ASHRAE compliant ventilation was altered. In cooling, the only ventilation was from the whole house fans. In heating, the ASHRAE compliant exhaust ventilation was used continuously.
- A four-head ducted multi-split (variable speed) heat pump was operated in a three-way round robin with the reference and house systems.

## Retrofit Year 2 Results

This section describes the results of the Retrofit Year 2 based on the Sacramento/Stockton weather file.

- Roof retrofit and passive ventilation. Insulating roof tile adhesive (measure #1) and passive ventilation provided an estimated 112 kWh savings or 14 percent of the reference system cooling use. See Figure 65.

**Figure 65: Caleb – Insulating Roof Tile Adhesive Cooling Energy Savings**

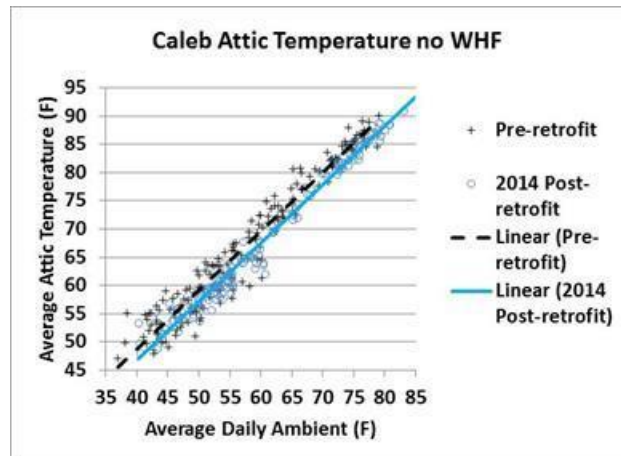


Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

In the winter, the roof tile insulation and the additional passive attic ventilation increased the house heat loss. The additional heat loss is estimated to be 614 kWh (9 percent).

The passive venting and the tile insulation dropped the 24-hour average attic temperature by about 2° F in both summer and winter. Figure 66 compares the baseline year data to the 2014 post-retrofit data. It excludes data for days when the whole house fans were operating.

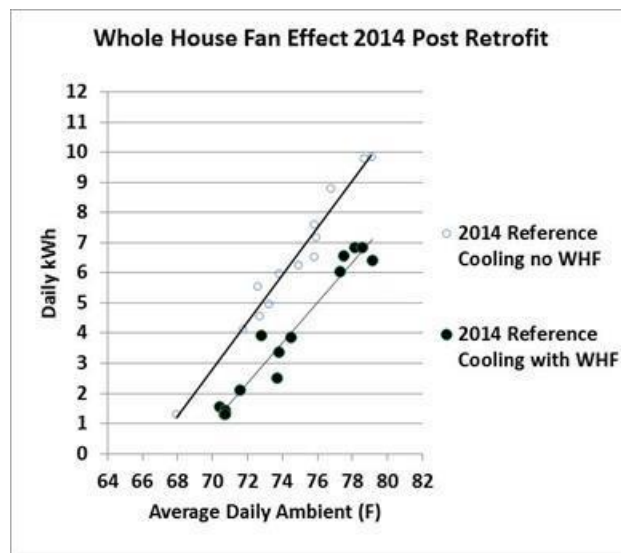
**Figure 66: Caleb – Attic Temperature Reduction from Roof Tile Insulation and Passive Ventilation**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

- Whole house fans. The whole house fans (measure #11) operated with time and temperature control (dawn to 11 p.m. with at least 4.5°F lower outside temperature). The whole house fan operation reduced air conditioning energy use between 220 and 270 kWh for reference and house air conditioners. See Figure 67.

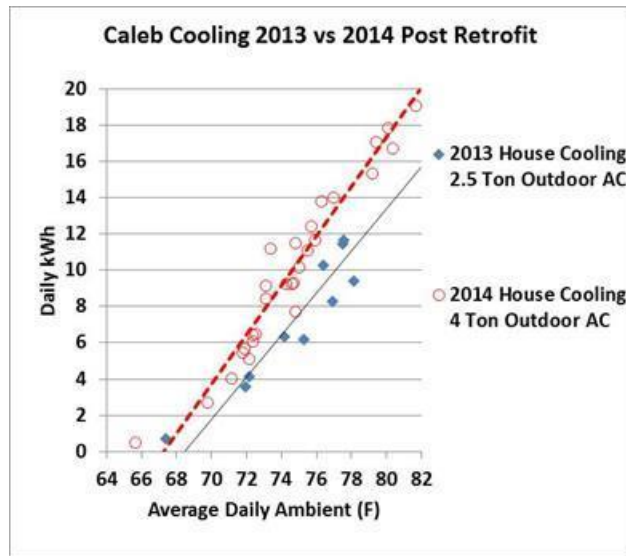
**Figure 67: Caleb – Whole House Fans Energy Savings**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

- AC system modifications. The downsized (2.5 ton) air conditioner condensing unit was replaced by the original 4 ton unit (measure #3). This increased the annual cooling energy use by 300 to 350 kWh (30+ percent increase). See Figure 68.

**Figure 68: Caleb – Cooling Energy Use Increase 4 Ton Versus 2.5 Ton Air Conditioner**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

# CHAPTER 4:

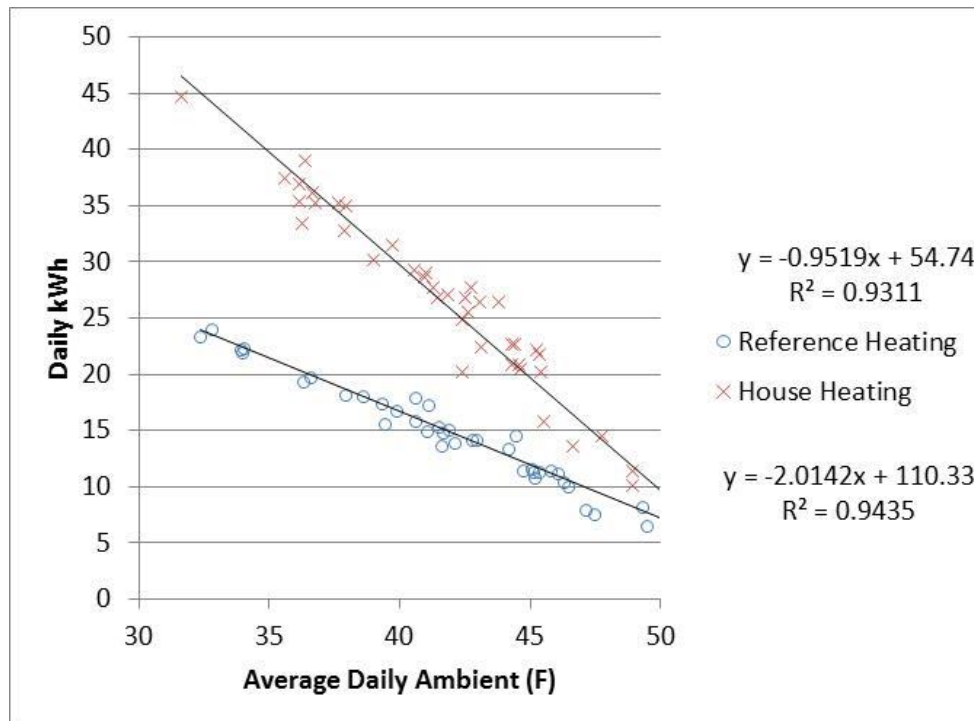
## Results and Discussion of First Retrofit Packages

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### Heating Use Before Installing the First Retrofit Packages

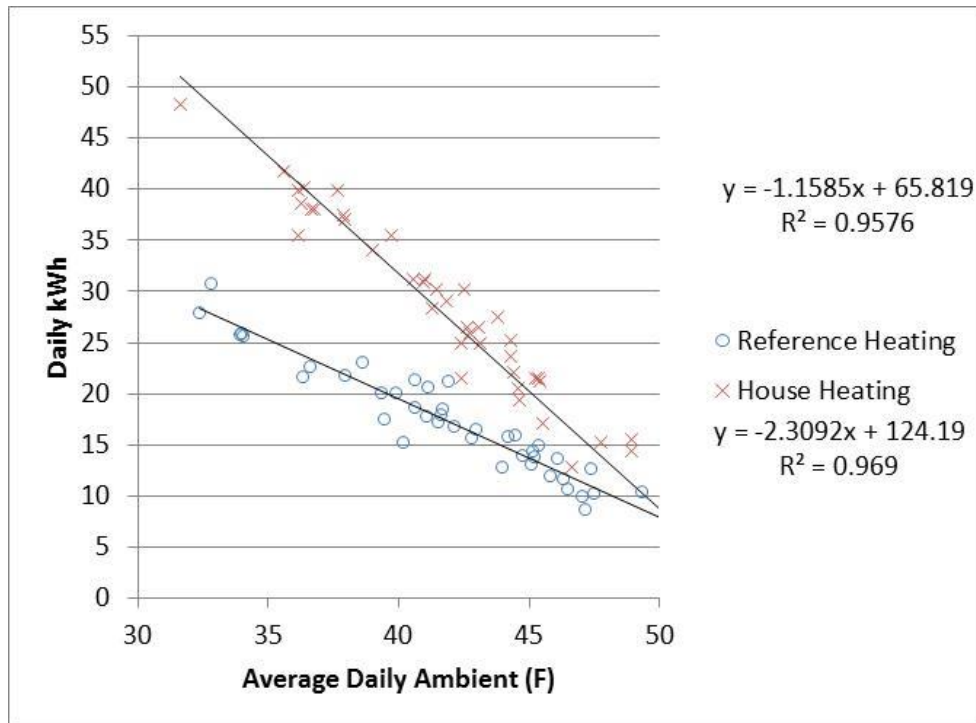
Figure 69 – Figure 72 show the energy use of the baseline house heating system and the reference heating system for each research house during the first winter (prior to installation of the first retrofit packages). The gas usage of the furnaces has been converted to equivalent kWh (1 therm = 29.3 kWh) and added to the furnace fan kWh to facilitate the comparison. Each plot shows the daily heating energy use versus the average outdoor temperature for each day where the baseline system and the reference systems provided the heat.

**Figure 69: Grange – Daily Kilowatt-hours, Winter 2012–2013**



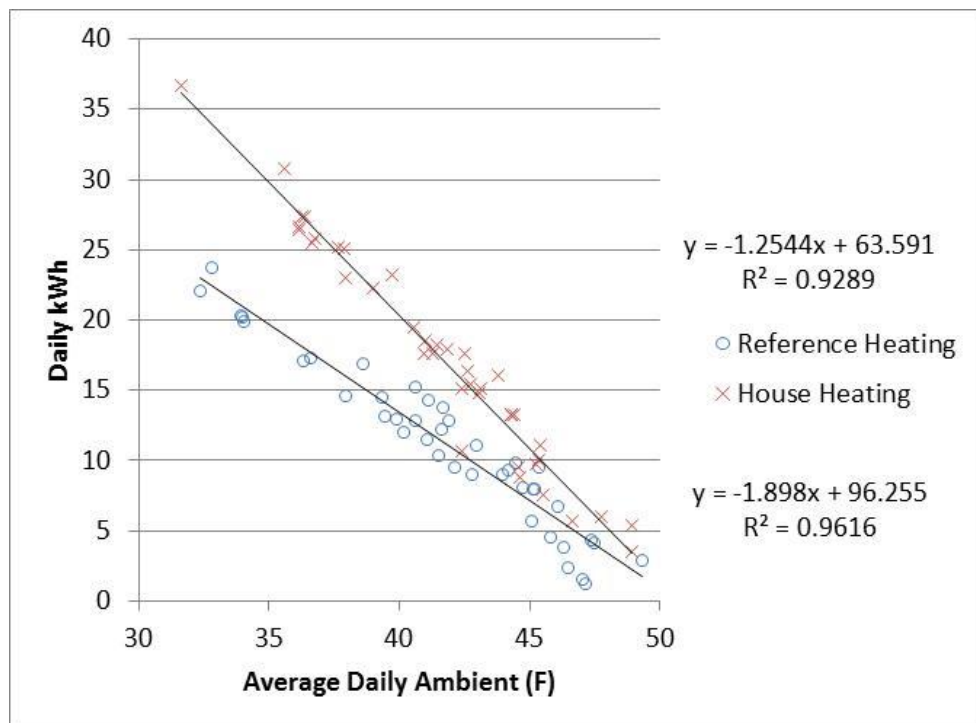
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 70: Mayfair – Daily Kilowatt-hours, Winter 2012–2013**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

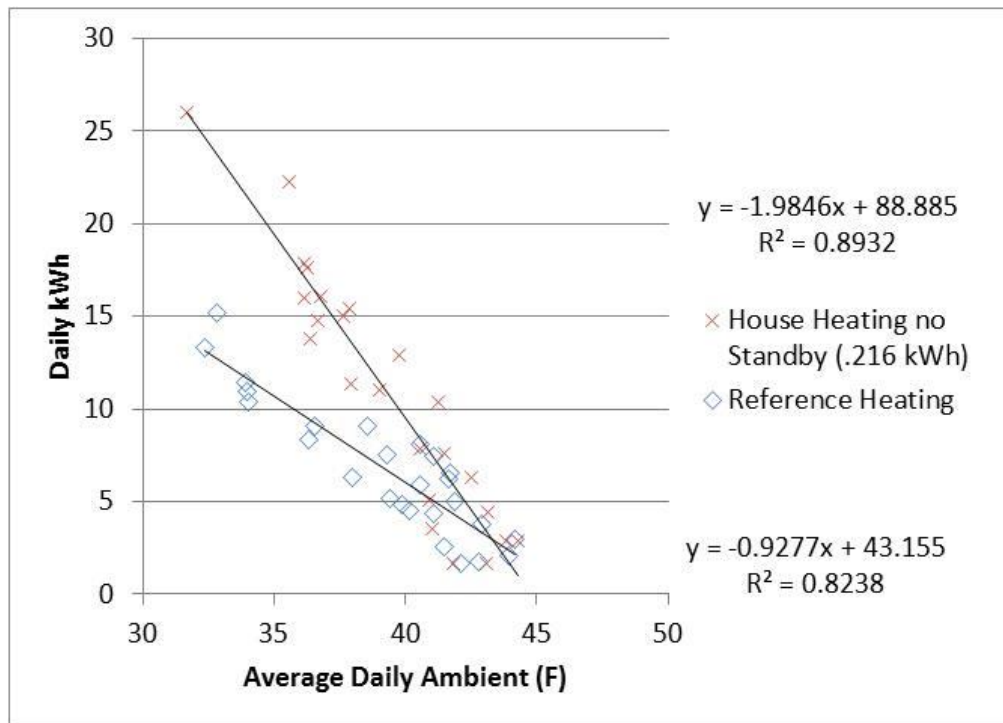
**Figure 71: Fidelia – Daily Kilowatt-hours, Winter 2012–2013**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood



**Figure 72: Caleb – Daily Kilowatt-hours, Winter 2012 – 2013**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

In all cases, the site energy use is lower with the electric resistance heaters in the rooms. The electric resistance heating is 100 percent efficient at the site. The furnaces have the losses inherent in the furnace and the duct losses. The overall site energy efficiency of the heating system at a particular average outdoor temperature can be estimated as the energy use of the reference system divided by the energy use of the house system. The furnace and duct site efficiencies for a winter day with an average 35°F outdoor temperature are shown in Table 14. Fidelia has a substantially higher house heating system efficiency than the other houses. At the same time the total heating energy use also depends on the balance temperature, which is different between the reference with room heaters and the ducted furnace systems. Table 14 also shows the heating balance temperatures.

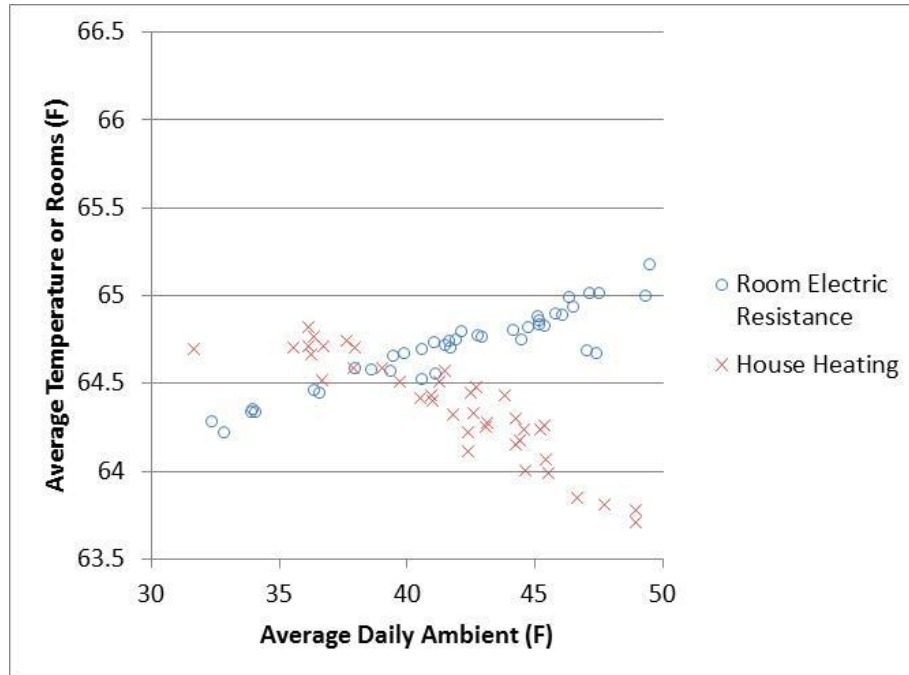
**Table 14: House Heating System Site-Energy Efficiency at 35°F Daily Average Ambient and Heating Balance Temperatures**

Metric	Grange	Mayfair	Fidelia	Caleb
House System Heating Efficiency	53.8%	58.3%	66.0%	55.0%
House System Balance Temperature	54.8°F	53.8 °F	50.7°F	44.8°F
Reference System Balance Temperature	57.5°F	56.8°F	50.7°F	46.5°F

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

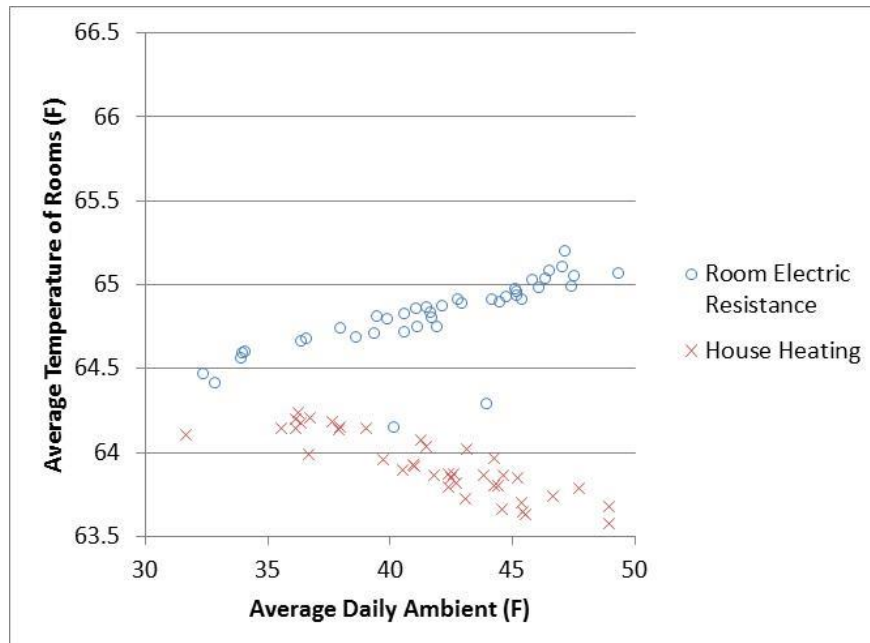
Figure 73 – Figure 76 show indoor temperatures during the first winter for each house. The reference systems (room electric resistance heaters) kept the houses at more uniform temperatures than the baseline heating system.

**Figure 73: Grange – Indoor Temperatures, Winter 2012–2013**



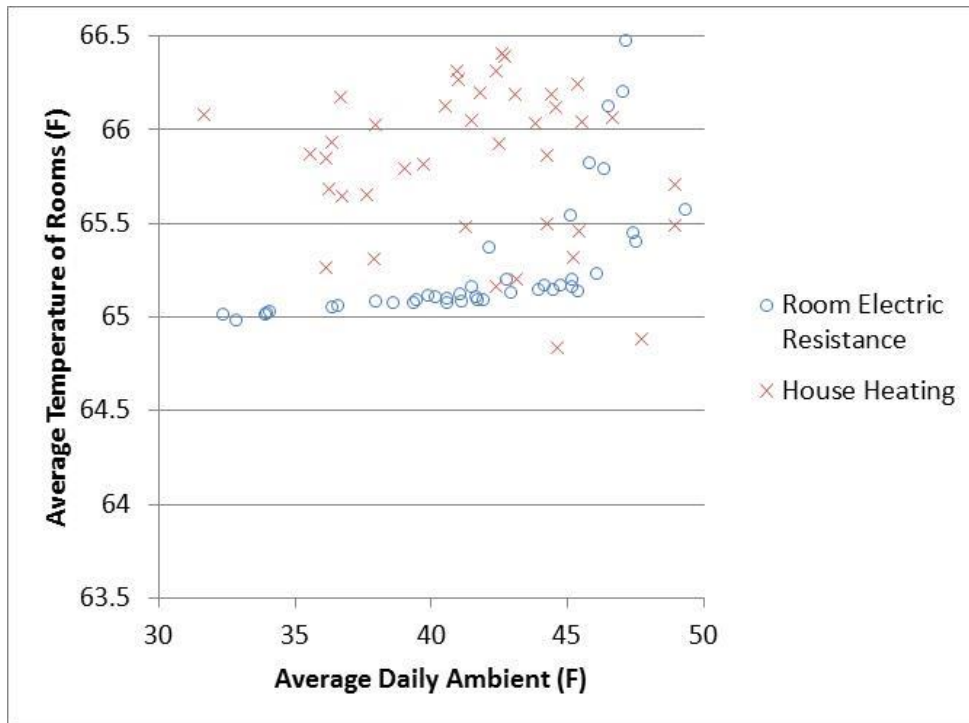
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 74: Mayfair – Indoor Temperatures, Winter 2012–2103**



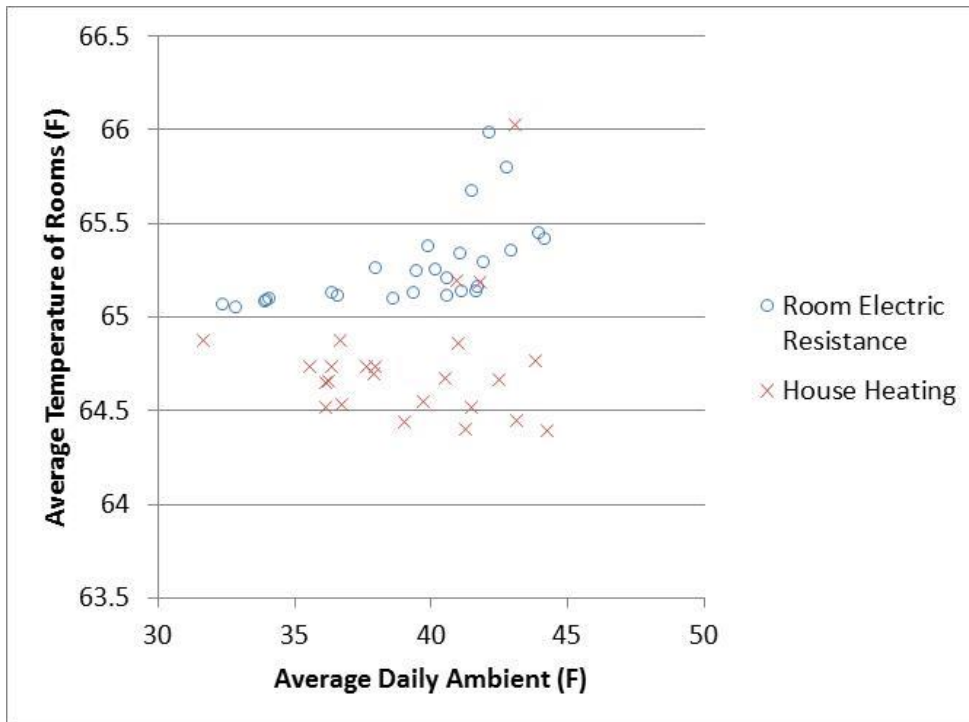
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 75: Fidelia – Indoor Temperatures, Winter 2012–2013**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 76: Caleb – Indoor Temperatures, Winter 2012–2013**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

The variability in the house internal temperatures at Fidelia is a "feature" of the two-story house with a single zone system.

## Cooling Use Before Installing the First Retrofit Packages

Figure 77 – Figure 80 show cooling use of the baseline house cooling system and the reference cooling system for each research house during the first summer prior to installation of the first retrofit packages.

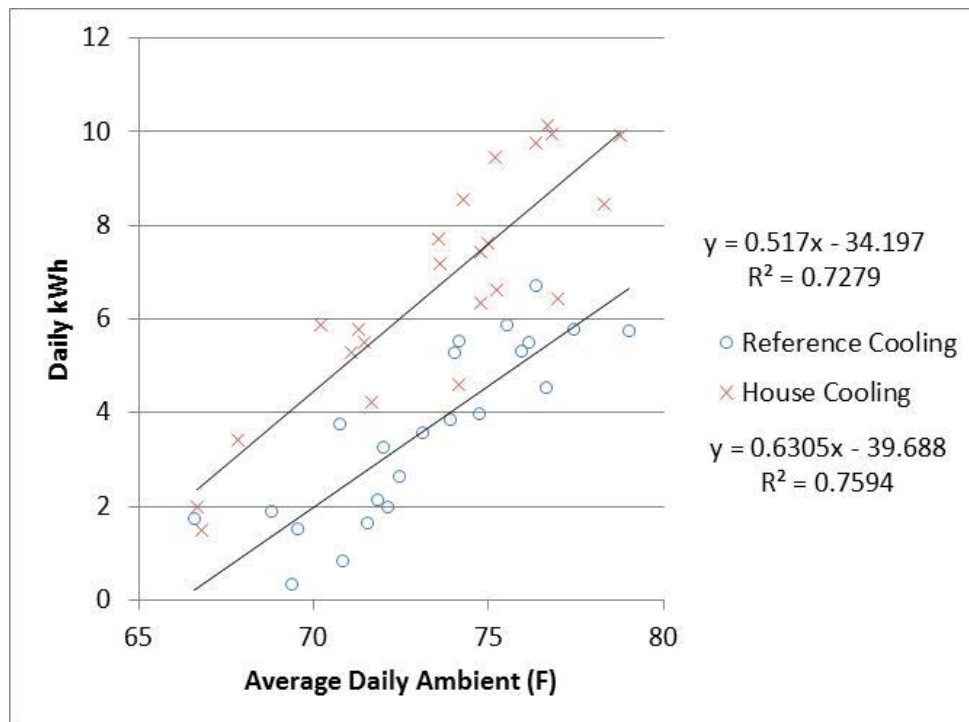
Note the difference in cooling balance temperatures between the systems with ducts in the attic (house cooling) and the ducts inside the conditioned space (reference cooling). The lower balance temperature with ducts in the attic indicates that the air conditioner has to come on sooner to keep the house cool. The baseline balance temperatures are shown in Table 15.

**Table 15: Baseline Cooling Balance Points**

System	Grange	Mayfair	Fidelia	Caleb
House Cooling	62.9°F	64.4°F	61.7°F	62.4°F
Reference Cooling	66.1°F	66.3°F	65.2°F	63.3°F

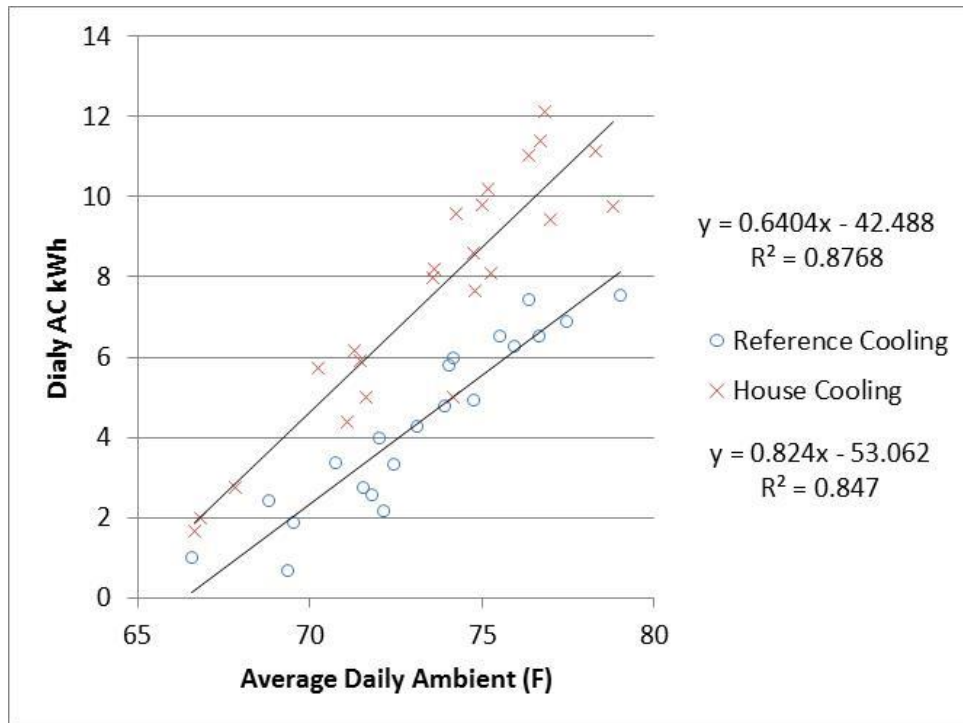
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 77: Grange – House and Reference Systems Daily Kilowatt-hours, Summer 2012**



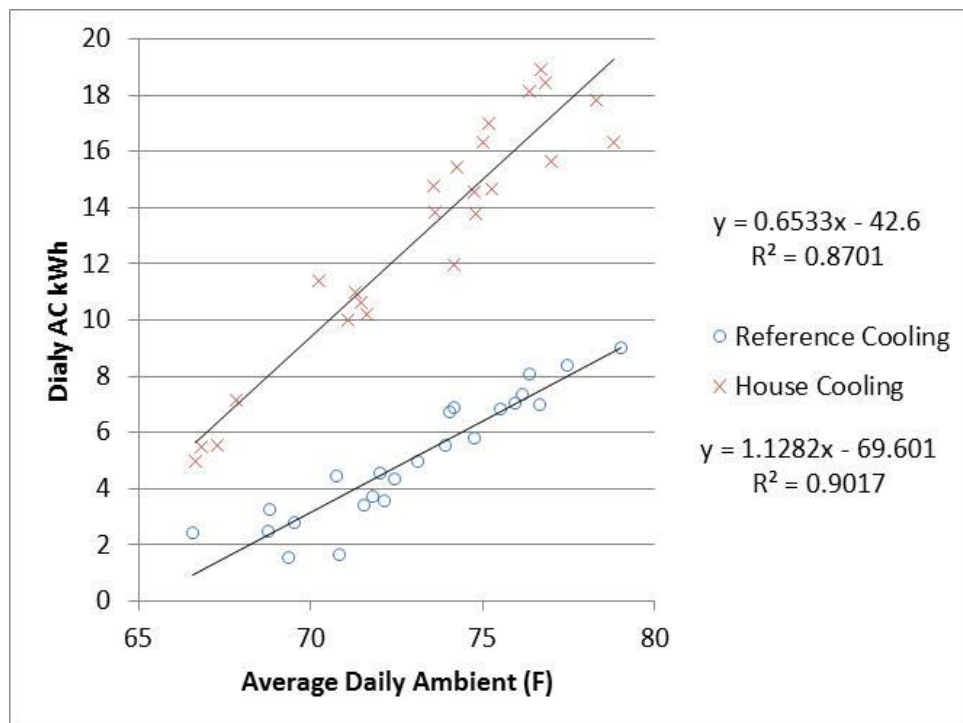
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 78: Mayfair – House and Reference Systems Daily Kilowatt-hours, Summer 2012**



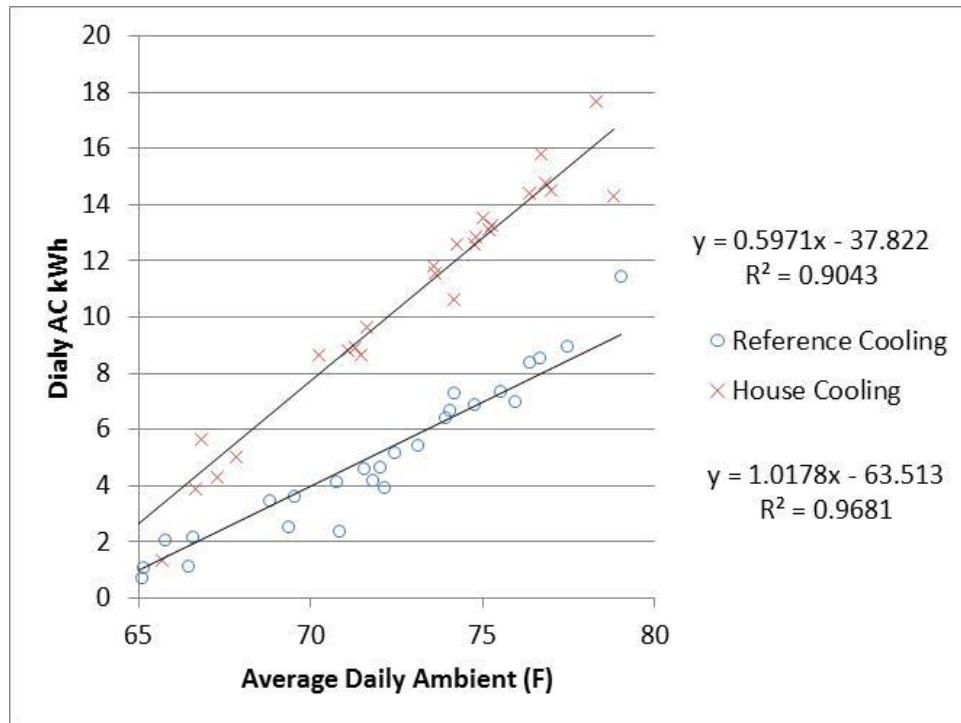
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 79: Fidelia – House and Reference Systems Daily Kilowatt-hours, Summer 2012**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 80: Caleb – House and Reference Systems Daily Kilowatt-hours, Summer 2012**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

Figure 77 – Figure 89 illustrate both the lower cooling balance points of the house systems and their higher rate of energy use. The efficiencies of the house systems relative to the reference systems (within conditioned space), standardized to the 2013 CEC Sacramento weather file, are shown in Table 16.

**Table 16: House Air Conditioning and Duct Cooling Efficiency Relative to Reference System**

Grange	Mayfair	Fidelia	Caleb
57%	61%	40%	53%

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

Notably, the Fidelia house had the most efficient baseline house heating system but the least efficient house cooling system.

## House Cooling System Efficiencies Before and After First Retrofit Packages

Figure 81 – Figure 84 show energy use of the house cooling system and the reference cooling system for each research house during the first and second summer (before and after installation of the first retrofit packages).

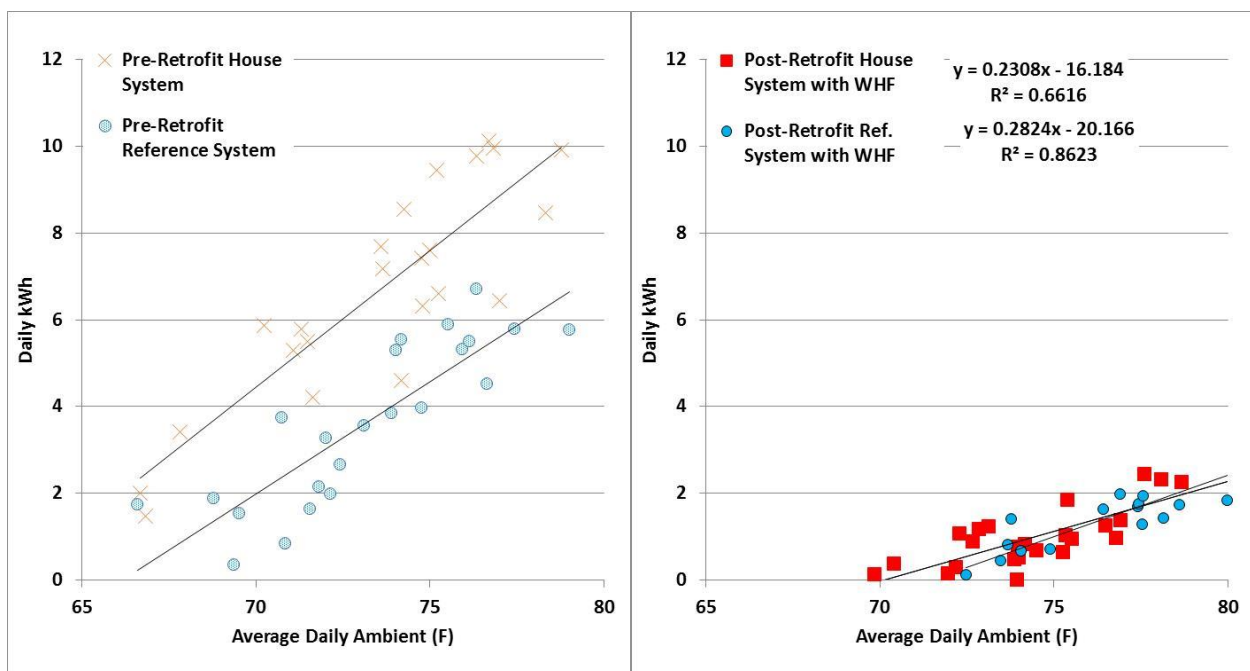
The improvements to the house systems brought them much closer to the reference systems with the ducts inside the conditioned space. The hot dry air conditioning (HDAC) retrofits include lower low resistance duct systems (except Caleb) and smaller compressors. Both of these retrofits contribute to the higher airflow per ton and better performance in the dry climate of California's Central Valley.

Grange (Figure 81) has a new super-insulated, low-surface-area duct system. The air conditioner was not replaced, but a 1-ton compressor replaced the original 2.5-ton compressor. The evaporator coil airflow increased from 219 CFM per ton to 540 CFM per ton.

Now the house system in Grange, within experimental error, is identical to the reference system.

Mayfair has a new super-insulated duct system and a 1.5 ton compressor replaced the 2.5 ton compressor in the existing rooftop package air conditioner. The evaporator coil airflow improved from 362 CFM per ton to 612 CFM per ton.

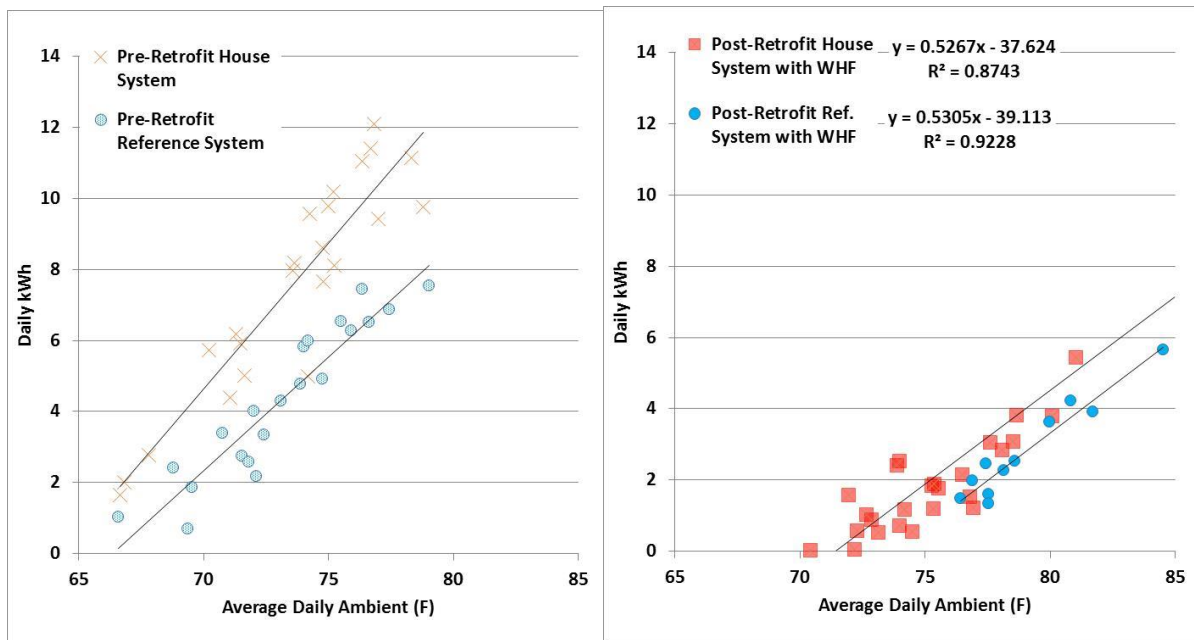
**Figure 81: Grange – House and Reference Systems Daily Kilowatt-hours, Summers 2012 and 2013**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood



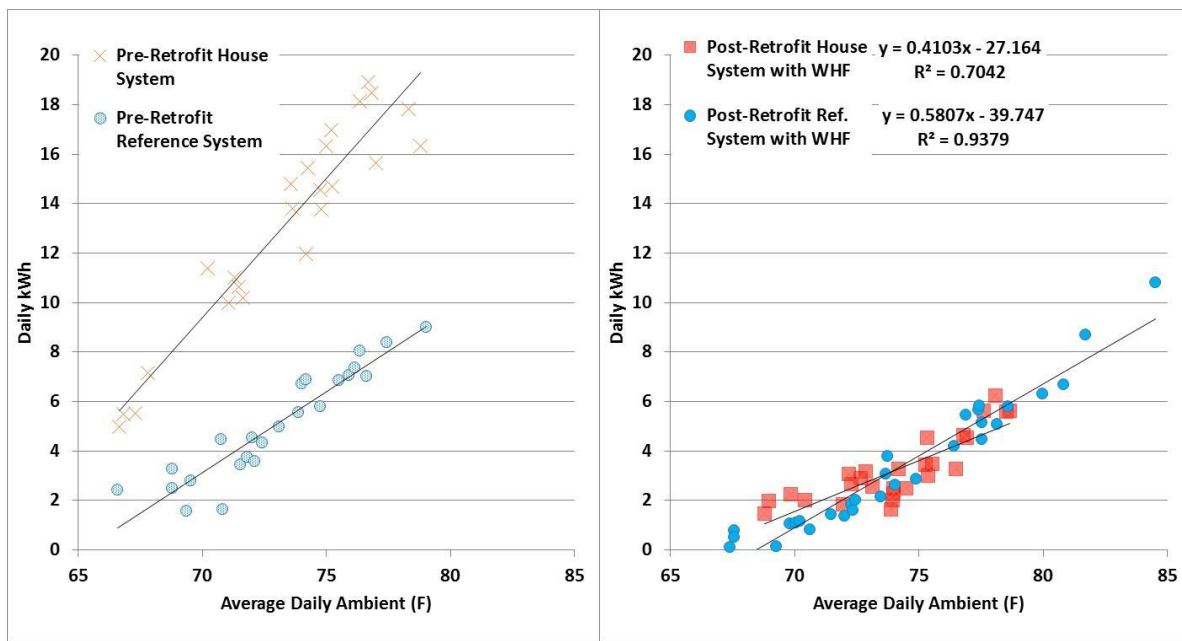
**Figure 82: Mayfair – House and Reference Systems Daily Kilowatt-hours, Summers 2012 and 2013**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

Fidelia (Figure 83) now has a house air conditioning system that is equivalent to the reference system contained within the conditioned space. All the ducts supplying the top story have been moved inside as have the ducts for the first story that ran through a lower level attic. The single zone duct system was converted to a capacity shift zoning system and the 3.5 ton EER 9 AC was replaced with a 1.5 ton EER 12.5 heat pump.

**Figure 83: Fidelia – House and Reference Systems Daily Kilowatt-hours, Summers 2012 and 2013**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

Caleb (Figure 84) had the air conditioning system retrofitted by changing from standard zoning to capacity shift zoning. A new 2.5 ton condensing unit replaced the existing 4 ton condensing unit. The indoor coil and air handler remained unchanged. The new rated condensing unit EER was 19 percent higher than the existing unit. The evaporator coil airflow was increased from 215 CFM per ton to 443 CFM per ton.

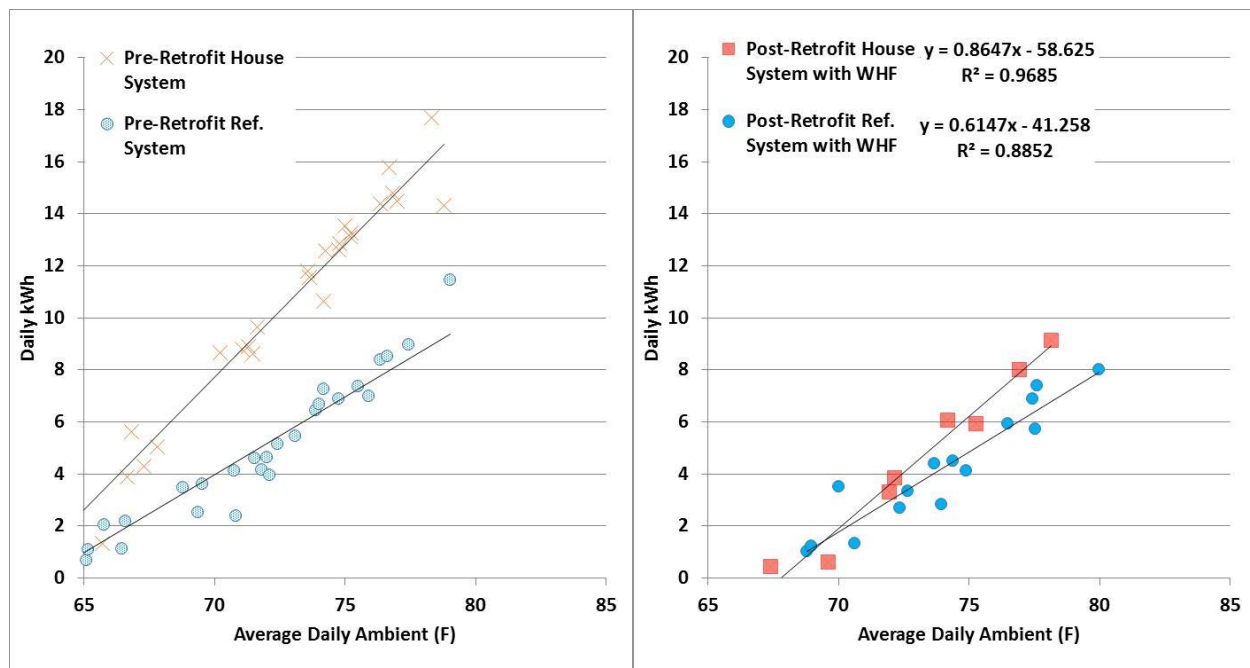
The pre-retrofit and post-retrofit efficiencies of the house systems relative to the reference systems, standardized to the 2013 Energy Commission Sacramento weather file are shown in Table 17. The Fidelia system that began as the least efficient system became the most efficient system.

**Table 17: House AC and Duct Cooling Efficiency (Percent of Reference Air Conditioning)**

	Grange	Mayfair	Fidelia	Caleb
Pre-Retrofit	57%	61%	40%	53%
Post-Retrofit	84%	91%	117%	73%

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 84: Caleb – House and Reference Systems Daily Kilowatt-hours, Summers 2012 and 2013**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Cooling Impact of First Year Retrofit Shell and Whole House Fan Measures

Figure 85 – Figure 88 compare the cooling use of the reference system before and after the first retrofit packages. Since the reference cooling system was not changed, the differences in usage are due to retrofit items not associated with the house cooling system. These changes include changes to the building shell as well as the addition of whole house fans and (the negative effect of) ASHRAE Standard 62.2 ventilation.

Note the difference in estimated balance temperatures between pre- and post-retrofit. The higher balance points after the retrofits indicate that the air conditioner does not come on until a higher outdoor temperature to keep the house equally cool. The estimated reference cooling balance points are shown in Table 18.

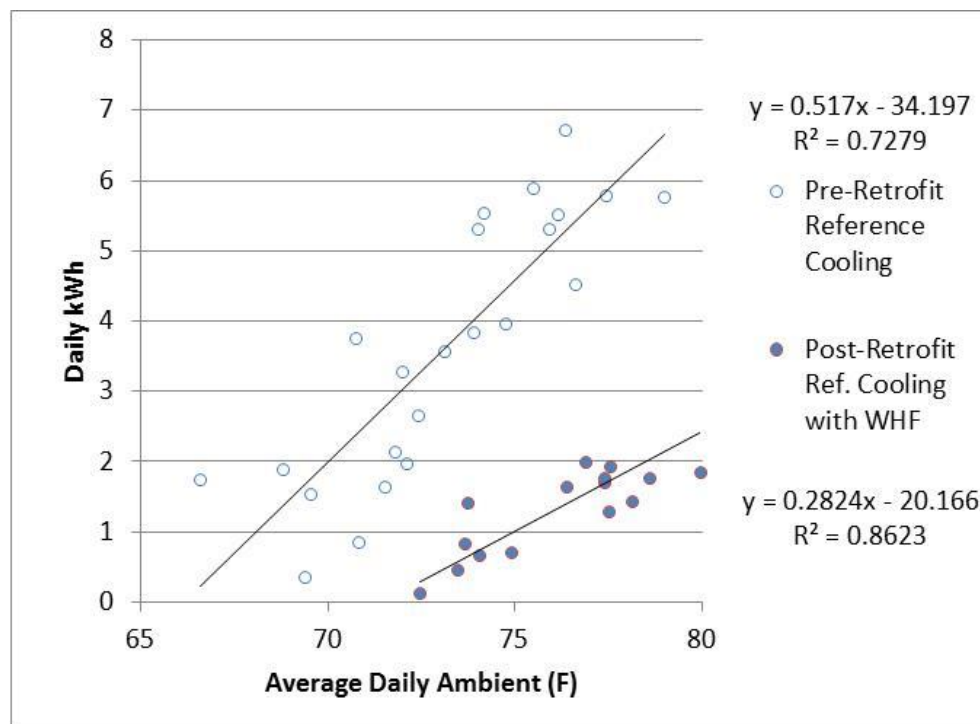
**Table 18: Reference Cooling Balance Points**

	Grange	Mayfair	Fidelia	Caleb
Pre-Retrofit	66.2°F	66.4°F	65.2°F	63.3°F
Post-Retrofit	71.5°F	73.7°F	68.5°F	68.1°F

**Note: Post-retrofit balance temperatures are with the whole house fan operating.**

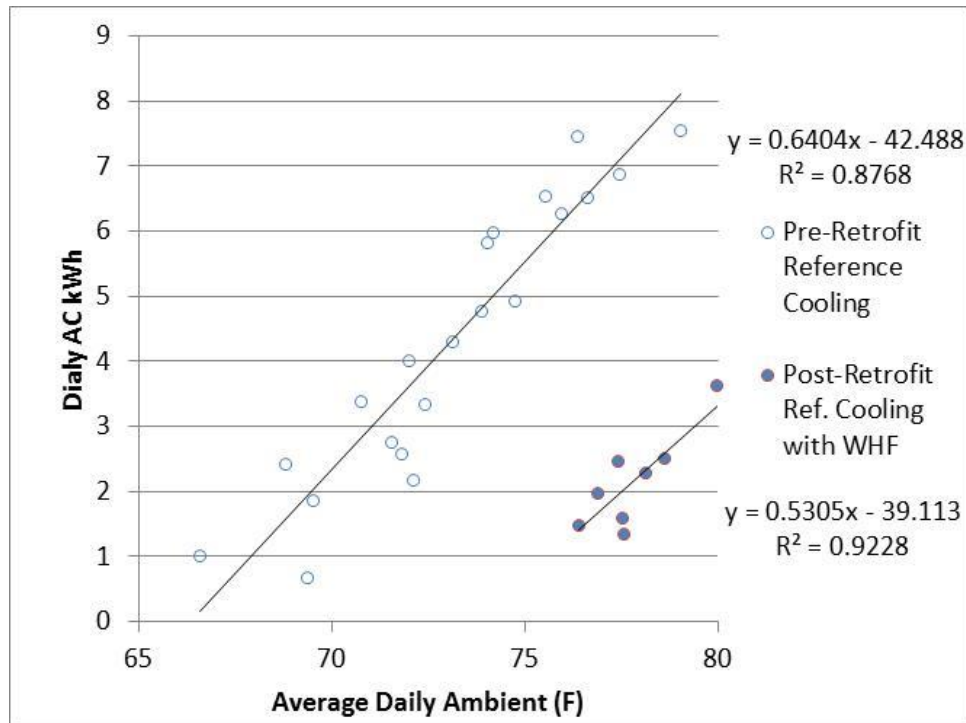
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 85: Grange – Reference System Pre/Post Daily Cooling Kilowatt-hours**



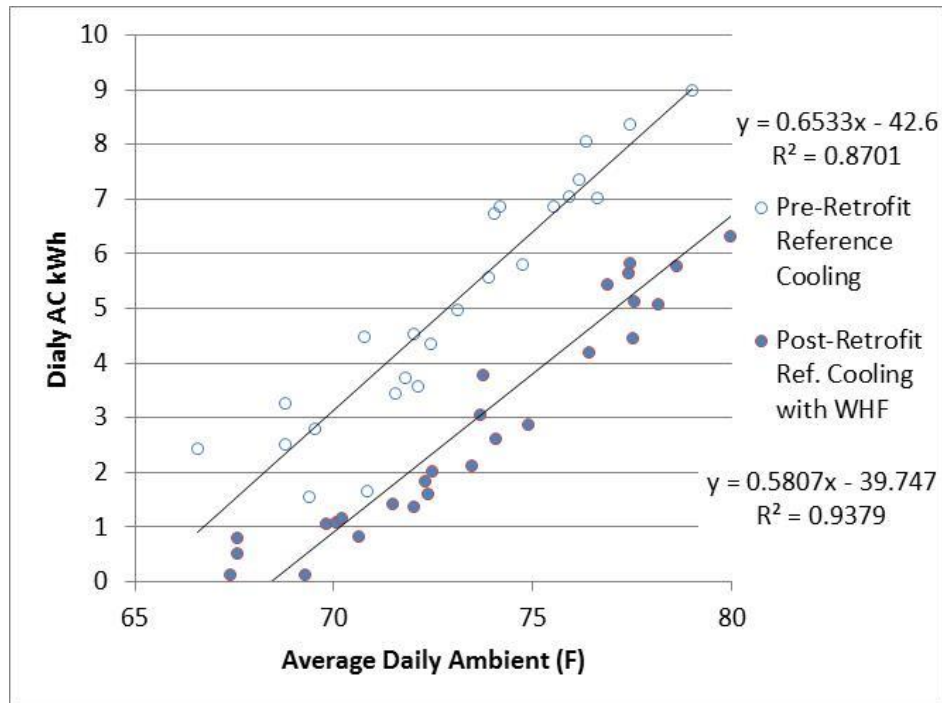
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 86: Mayfair – Reference System Pre/Post Daily Cooling Kilowatt-hours**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

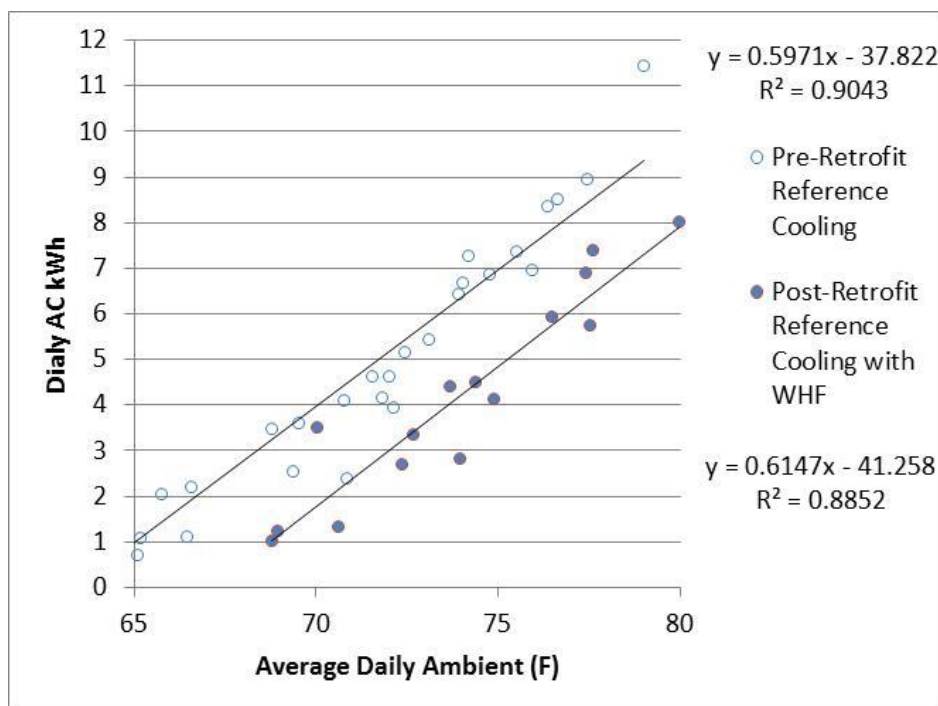
**Figure 87: Fidelia – Reference System Pre/Post Daily Cooling Kilowatt-hours**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

At Caleb (Figure 88), the newest house, three changes cause the change in reference system kWh usage: foam beneath roof tiles, whole house fan, and ASHRAE 62.2 ventilation.

**Figure 88: Caleb – Reference System Pre/Post Daily Cooling Kilowatt-hours**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

The cooling use changes experienced with the reference systems between the pre- and post-retrofit scenarios show the changes in energy consumption due to shell retrofits, whole house fan operation, and IAQ fan operation. The reduction in AC energy consumption is shown in Table 19.

**Table 19: Air Conditioning Gross Energy Reduction from Retrofit Year 1 Shell Improvements**

Grange	Mayfair	Fidelia	Caleb
80%	70%	43%	41%

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## House Cooling Use After Installing the First Retrofit Packages

Figure 89 – Figure 92 compare the cooling use of the house system before and after the first retrofit packages. The differences in usage are due to all the retrofit items including load reductions and improvements in AC system efficiency.

Note the difference in estimated balance temperatures between pre- and post-retrofit. The higher balance points after the retrofits indicate that the air conditioner does not come on until a higher outdoor temperature to keep the house equally cool. The estimated reference cooling balance points are shown in Table 20.

**Table 20: House System Cooling Balance Points Before and After Retrofit Year 1**

	Grange	Mayfair	Fidelia	Caleb
Pre-Retrofit	62.9°F	64.4 °F	61.7°F	62.4°F
Post-Retrofit	70.1°F	71.4°F	68.4°F	67.8°F

**Note: Post-retrofit balance temperatures are with the whole house fan operating.**

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

The cooling usage changes experienced with the house systems between the pre- and post-retrofit scenarios show the changes in both load and AC efficiency. Every house met the 50 percent to 75 percent energy reduction goal of the project.

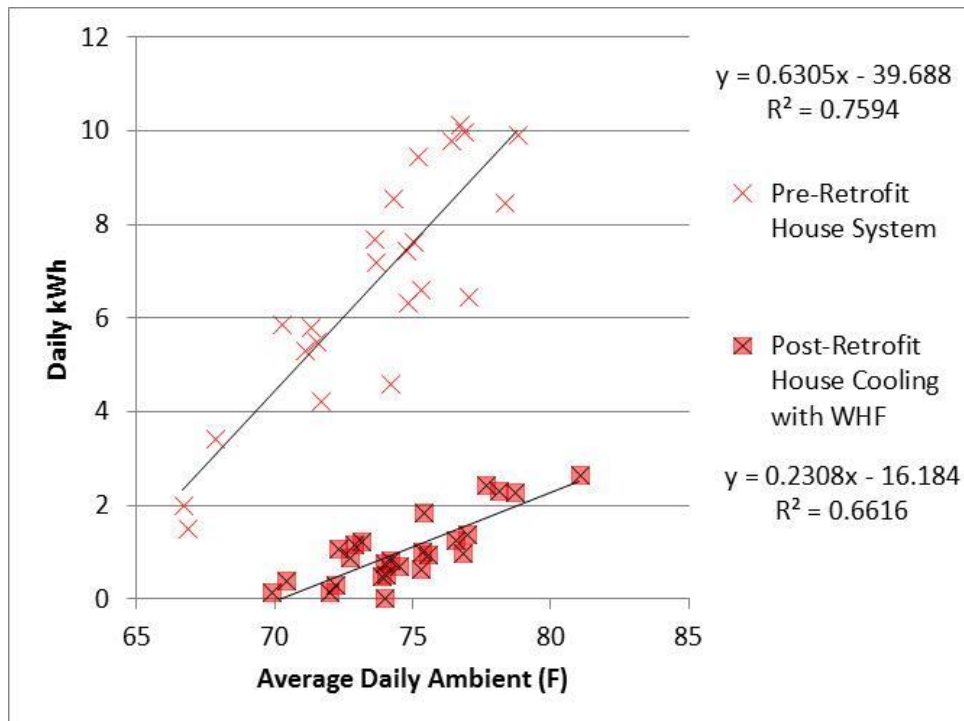
The reductions in house AC energy usage are shown in Table 21.

**Table 21: House Air Conditioning Usage Reduction**

Grange	Mayfair	Fidelia	Caleb
87%	80%	80%	58%

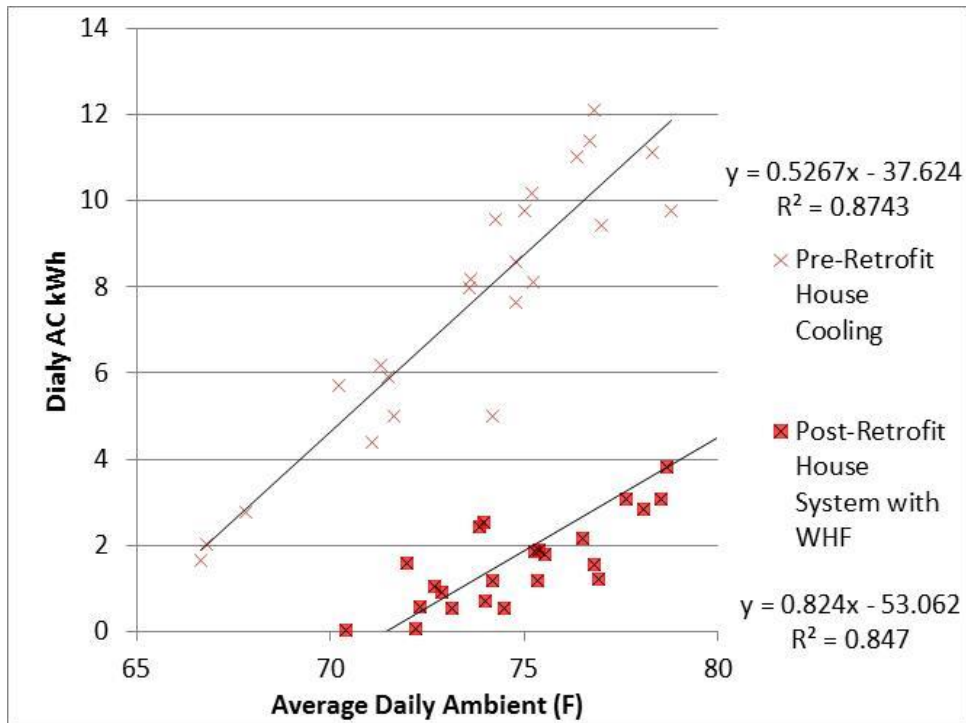
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 89: Grange – House System Pre/Post Daily Cooling Kilowatt-hours**



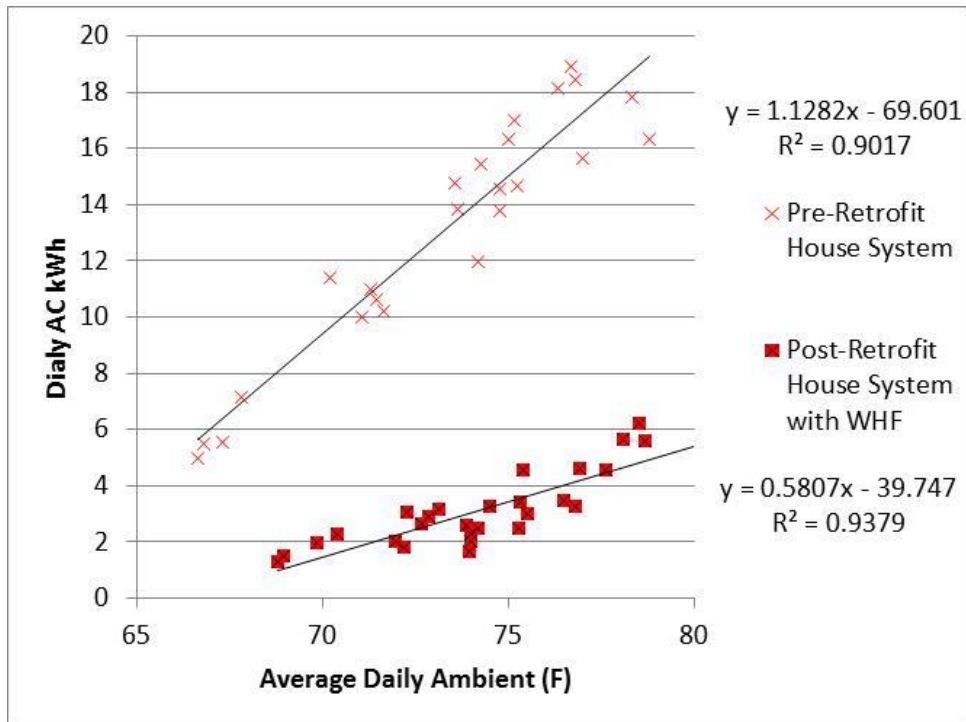
Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Figure 90: Mayfair – House System Pre/Post Daily Cooling Kilowatt-hours**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

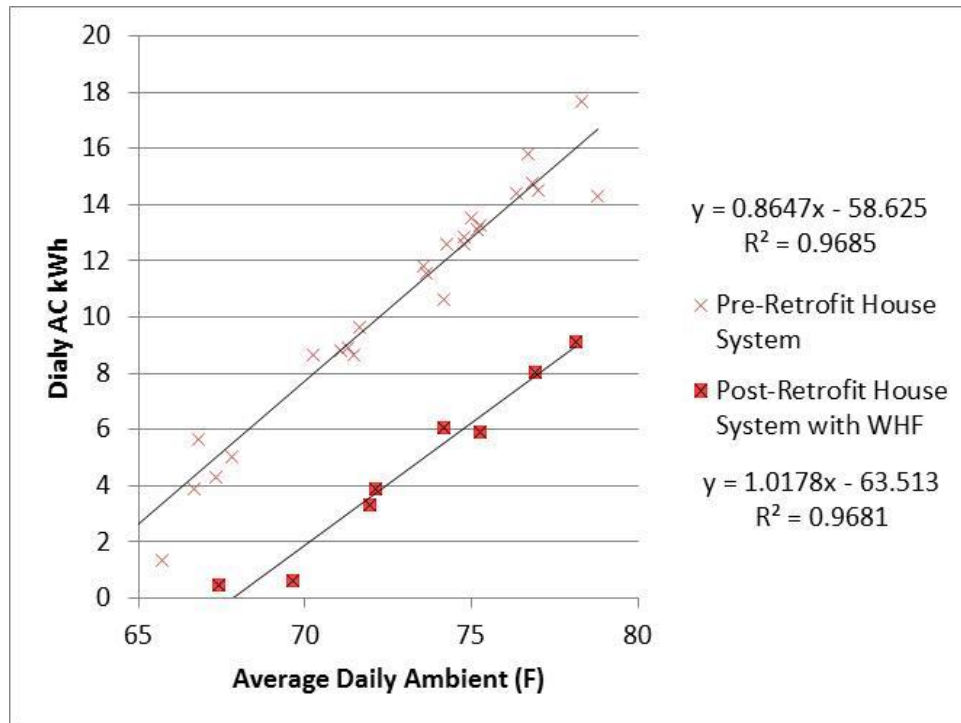
**Figure 91: Fidelia – House System Pre/Post Daily Cooling Kilowatt-hours**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood



**Figure 92: Caleb – House System Pre/Post Daily Cooling Kilowatt-hours**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Whole House Fan Effect

The whole house fans (WHF) were controlled by the inside/outside temperature differential, the inside temperature (for comfort), and the time of day (corresponding to the times that occupants might open windows).

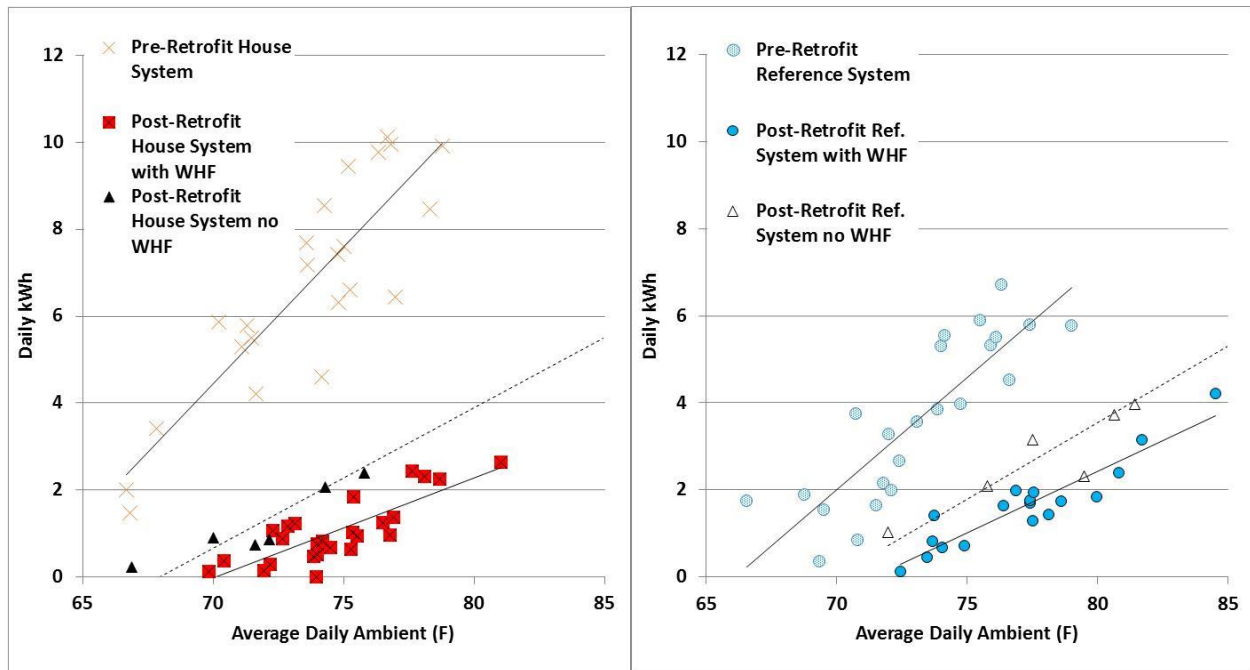
### House Systems and Reference Systems

Figure 93 – Figure 96 show cooling use with and without the whole house fans operating. The pre-retrofit data are all without whole house fans, and they are included to provide an indication of the portion of the total cooling energy reduction might be due to the use of whole house fans. The flip/flop of whole house fans took place on four-day intervals overlapping the two-day intervals upon which the house and reference systems flip.

These whole house fan retrofits are premium products with multiple fans, an automatic control, and an interlocked outdoor air damper with a filtered intake. These were chosen since the houses are unoccupied and they could be controlled by the monitoring computer. The same energy savings can be obtained with less expensive conventional whole house fans.

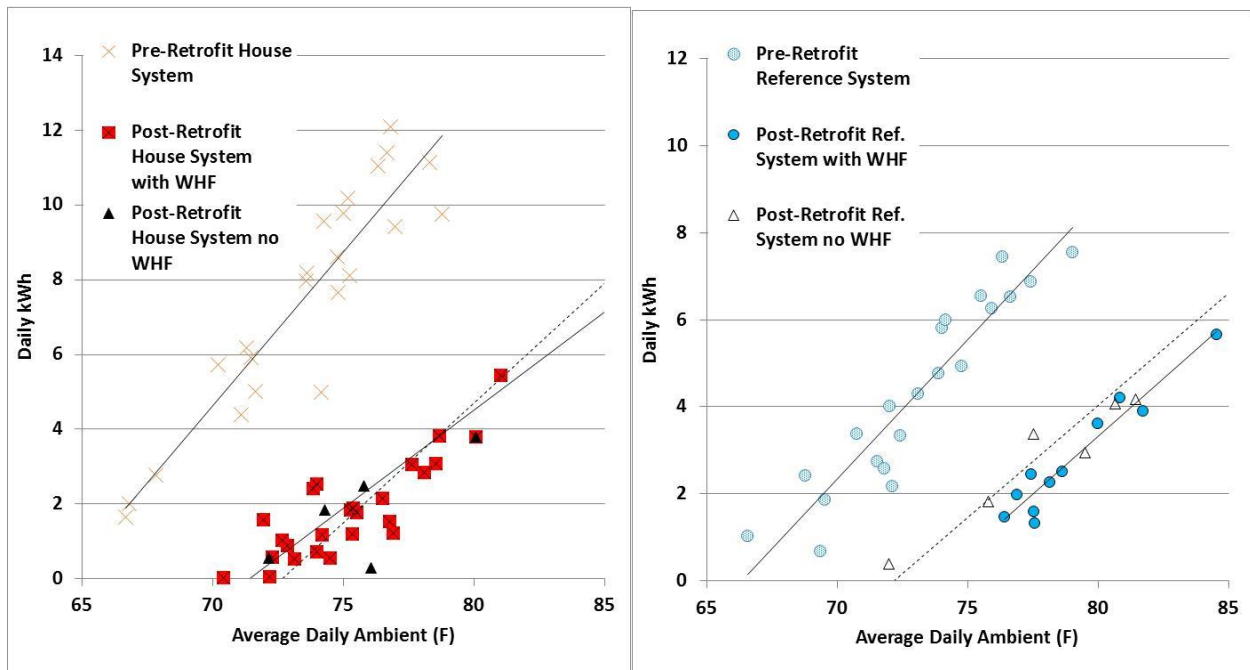
The data in Figure 93 indicate a major cooling effect on the Grange house.

**Figure 93: Grange – House and Reference Systems Daily Kilowatt-hours – Whole House Fan Effect**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

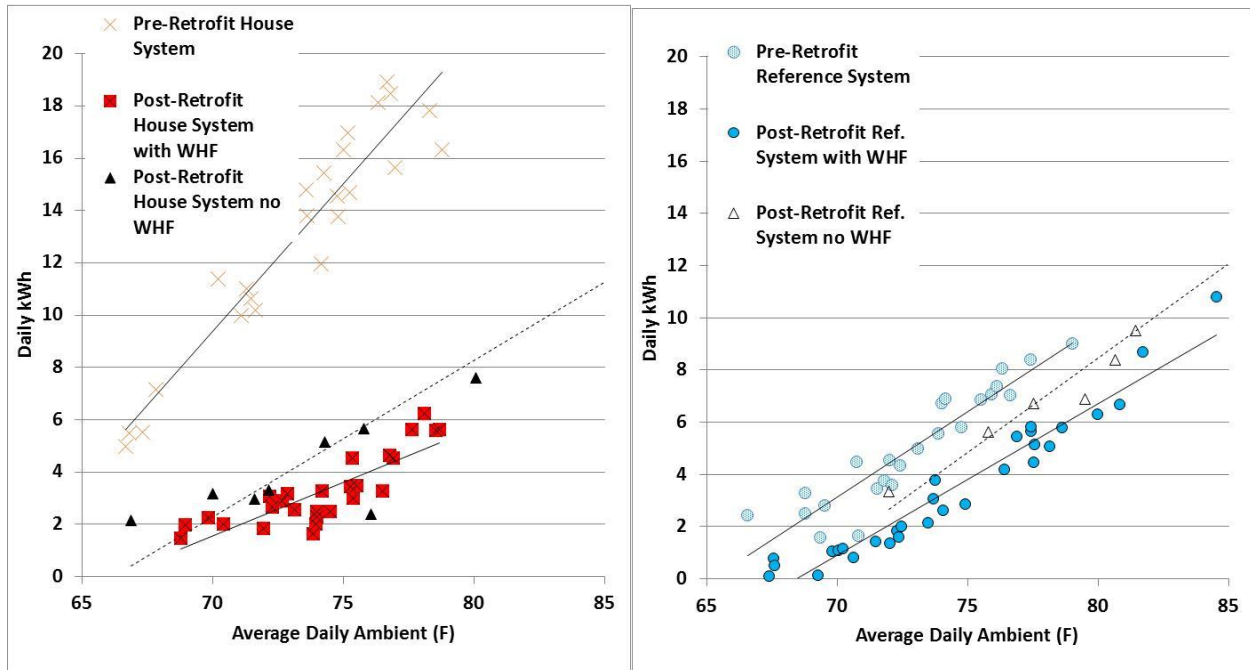
**Figure 94: Mayfair – House and Reference Systems Daily Kilowatt-hours – Whole House Fan Effect**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

The data in Figure 95 indicate that the whole house fans may be responsible for as much as half the cooling load reduction on the Fidelia house, as seen in the right-hand graph of daily cooling energy when the reference system is running.

**Figure 95: Fidelia – House and Reference Systems Daily Kilowatt-hours – Whole House Fan Effect**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

The data in Figure 96 indicate that the whole house fans may be responsible for the majority of the cooling load reduction on the Caleb house.

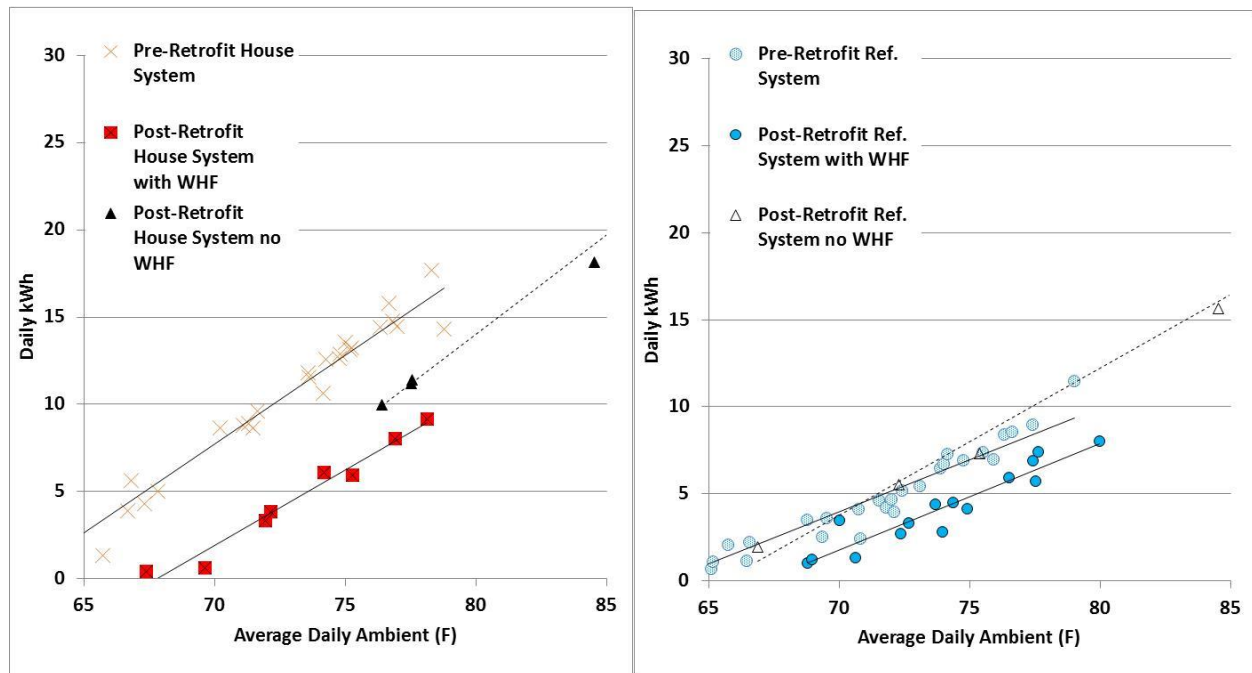
With the exception of Mayfair in the house system mode, all operations indicate that the whole house fans greatly reduced the cooling load on these houses, accounting for from 22 percent to 46 percent of the remaining<sup>12</sup> cooling load (Grange 46 percent, Mayfair 28 percent, Fidelia 22 percent, and Caleb 28 percent). It is important to recall that these load reductions are on houses with substantially reduced total cooling load. When applied to houses with larger cooling loads, the percentage savings may be less.

## Multivariate Regression Results

The estimates shown on the figures are simple linear regressions of cooling energy consumption against average outdoor temperature for the day. The annual cooling savings estimates use multivariate regressions.

<sup>12</sup> Remaining after the other shell load reduction measures are implemented.

**Figure 96: Caleb – House and Reference Systems Daily Kilowatt-hours with and without Whole House Fan**



Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Annual Cooling and Heating Savings Estimates

Annual cooling energy savings were estimated by first estimating the gross cooling savings and then reducing the savings to account for the electricity consumed by the following equipment.

- Whole house fans.
- Zoning controller and dampers added to Fidelia.
- Crankcase heater at Fidelia.

### Gross Cooling Savings

The annual cooling usage was estimated by a multivariate regression<sup>13</sup> fit to the monitored data. Separate regressions were done for the data for the reference systems and the House systems. Several potential models were tested that included the following predictor variables:

- Daily Average Ambient Temperature (°F).
- Post Retrofit (0/1).
- Post Retrofit Daily Average Ambient Temperature (0/1 x °F).

<sup>13</sup> Regression is a process that produces a "curve fit" by minimizing the differences (errors) between the data and the equation for the "curve." Multivariate regression is a regression that fits the equation to multiple variables such as temperatures and the use or non-use of a whole house fan. Technical note – this method actually minimizes the square root of the sum of the squares of the errors.

- Whole House Fan On (0/1).
- Whole House Fan On Daily Average Ambient Temperature (0/1 x °F).
- IAQ Fan On (0/1).
- IAQ Fan On Daily Average Ambient Temperature (0/1 x °F).

These variables were tested in a variety of combinations as well as transformations to allow non-linearity (particularly against ambient temperatures). Hourly data were also tested using similar regression techniques. In the final analysis, the daily data are used: Daily Average Ambient, Post Retrofit (0/1), Post Retrofit Daily Average Ambient, IAQ Fan x Ambient, and Whole House Fan x Ambient. These provided stable, rational, and statistically defensible results. The hourly data provided results consistent with the daily data but with higher levels of uncertainty.

The regression fits were applied to the 2008 and 2013 Title 24 Sacramento weather files. The 2008 and 2013 files are markedly different. The 2008 file yields 1073 cooling degree days at a base of 63°F (CDD<sub>63</sub>), while the 2013 file yields 1422 CDD<sub>63</sub>, an increase of 32 percent.

The savings associated with the building shell retrofits and other load changes (whole house fans and IAQ fans) are estimated from the reference systems' regressions. The savings from the HVAC retrofits and the load changes together are estimated from the house systems' regressions. The savings from the HVAC retrofits alone are estimated by the equation:

$$Sav_{HVAC} = 1 - \frac{\left( \frac{UseHouseSystem_{post}}{UseRefSystem_{post}} \right)}{\left( \frac{UseHouseSystem_{pre}}{UseRefSystem_{pre}} \right)}$$

Table 22 – Table 29 show the annual space conditioning savings estimates for each house resulting from the first retrofit package. Note that with the lower temperature sensitive consumption, the constant electrical use of transformers and controls becomes noteworthy. The energy consumption of the transformers and controls occur all year.

**Table 22: Grange – Gross Cooling Percentage Use and Savings**

<b>Metric</b>	<b>Weather File</b>	
	<b>2008</b>	<b>2013</b>
House-System Efficiency Baseline Year (percent of Reference System use)	53%	57%
House-System Efficiency, Retrofit Year 1	82%	84%
Savings from all measures (based on house-system pre- and post-retrofit regression results)	90%	87%
Savings from HVAC Retrofits alone	36%	33%
Savings from Load Changes alone, including Shell Retrofits & WHF (based on Reference-system pre-and post-retrofit regression results)	84%	80%

**Notes:** Standby use not included. Reference system standby 43 kWh/year. House Standby 30 kWh/year. WHF kWh not included 16 kWh/year.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table 23: Grange – Gross Heating Percentage Use and Savings**

<b>Metric</b>	<b>Weather File</b>	
	<b>2008</b>	<b>2013</b>
House System Efficiency Baseline Year (percent of Reference System use)	65%	65%
House System Efficiency Retrofit Year 1 (percent of Reference System use)	67%	68%
Savings from Load Changes & HVAC Retrofits	59%	59%
Savings from HVAC Retrofits	3%	4%
Savings from Load Changes (Shell Retrofits)	64%	64%

**Notes:** Standby use not included. Reference system standby 0 kWh/year. House Standby 29 kWh/year.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table 24: Mayfair – Cooling Gross Percentage Use and Savings**

<b>Metric</b>	<b>Weather File</b>	
	<b>2008</b>	<b>2013</b>
House System Efficiency Baseline Year (percent of Reference System use)	58%	61%
House System Efficiency Retrofit Year 1	92%	91%
Savings from Shell & HVAC Retrofits	84%	80%
Savings from HVAC Retrofits	37%	33%
Savings from Shell Retrofits	75%	70%

**Notes:** Standby use not included. Reference system standby 43 kWh/year. House Standby 34 kWh/year. WHF kWh not included 13 kWh.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table 25: Mayfair – Heating Gross Percentage Use and Savings**

<b>Metric</b>	<b>Weather File</b>	
	<b>2008</b>	<b>2013</b>
House System Efficiency Baseline Year (percent of Reference System use)	83%	83%
House System Efficiency Retrofit Year 1	83%	83%
Savings from Shell & HVAC Retrofits	50%	50%
Savings from HVAC Retrofits	0%	0%
Savings from Shell Retrofits	58%	58%

**Notes:** Standby use not included. Reference system standby 0 kWh/year. House Standby 12 kWh/year.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood



**Table 26: Fidelia – Cooling Gross Percentage Use and Savings**

Metric	Weather File	
	2008	2013
House System Efficiency Baseline Year (percent of Reference System use)	38%	40%
House System Efficiency Retrofit Year (percent of Reference System use)	113%	117%
Savings from Shell & HVAC Retrofits	84%	80%
Savings from HVAC Retrofits	66%	65%
Savings from Shell Retrofits	52%	43%

**Notes:** Standby use not included. Reference system standby 44 kWh/year. House Standby 27 kWh/year. House standby retrofit year 1 174 kWh/year. WHF kWh not included. Retrofit Year 1 22 kWh/year, Retrofit Year 2 50 kWh/year.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table 27: Fidelia – Heating Gross Percentage Use and Savings**

Metric	Weather File	
	2008	2013
House System Efficiency Baseline Year (percent of Reference System use)	60%	60%
House System Efficiency Retrofit Year (Heat Pump COP)	3.78 COP	3.81 COP
Savings from Shell & HVAC Retrofits	88%	88%
Savings from HVAC Retrofits	84%	84%
Savings from Shell Retrofits	23%	23%

**Notes:** Standby use not included. Reference system standby 0 kWh/year. House Standby 26 kWh/year. House standby retrofit year 1 212 kWh/year.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table 28: Caleb – Cooling Gross Percentage Use and Savings**

Metric	Weather File	
	2008	2013
House System Efficiency Baseline Year (percent of Reference System use)	51%	53%
House System Efficiency Retrofit Year (percent of Reference System use)	73%	73%
Savings from Shell & HVAC Retrofits	66%	58%
Savings from HVAC Retrofits	30%	28%
Savings from Shell Retrofits	52%	41%

**Notes:** Standby use not included. Reference system 47 kWh/year, House Standby 41 kWh/year. WHF kWh not included 20 kWh/year.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table 29: Caleb – Heating Gross Percentage Use and Savings**

Metric	Weather File	
	2008	2013
House System Efficiency Baseline Year (percent of Reference System use)	75%	75%
House System Efficiency Retrofit Year (percent of Reference System use)	72%	72%
Savings from Shell & HVAC Retrofits with IAQ Fan Operating	-24%	-24%
Savings from HVAC Retrofits	-4%	-5%
Savings from Shell Retrofits	-4%	-4%

**Notes:** Standby use not included. Reference system 0 kWh/year, House Standby Baseline Year 39 kWh/year, Retrofit Year 1 47. Heating use increase due to use of IAQ fan.

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Energy Savings and Life Cycle Cost from Simulations

The pre- and post-retrofit homes (and variants) for each house were simulated using the Energy Commission's California Building Energy Code Compliance 2013 Residential Standards compliance software package to produce heating and cooling energy savings and life cycle costs representing typical occupancy and weather. These simulations are used to identify savings for individual measures. The regression analysis results based on measured performance provide savings estimates for only packages of measures. Domestic hot water, appliances, lighting and miscellaneous energy uses were not part of the CVRH experiment so they are excluded from these results.

The primary measure of energy in this analysis is time dependent valuation (TDV), calculated using the hourly societal value of energy for the Energy Commission's compliance weather files.<sup>14</sup> The present value of TDV energy savings were calculated per the current Energy Commission rules for life cycle costing for building Standards development (Architectural Energy Corporation. 2011). Those rules value lifetime energy savings at \$0.1732 per TDV kBtu of annual savings.

These simulations represent conditions similar to those measured in the home, as described earlier, with the following exceptions:

- The Energy Commission's compliance weather file for Climate Zone 12 (CTZ12S13b.CSW) was used instead of the measured weather data for Stockton for the experimental period.
- The Commission's standard internal gain assumptions were used instead of the actual internal gains that were produced during the experiments. Due to hardware limitations and errors the experimental internal gains were different from the standard internal gains.
- Windows in the simulations were opened according to the current Energy Commission rules to minimize cooling energy. Windows in the CVRH homes were never opened because the homes were unoccupied. This difference has the largest impact on the measured cooling in the pre-retrofit period. In the post-retrofit period the whole house fans provided cooling ventilation.
- The homes were simulated with normal levels of internal furnishings, but the CVRH experimental homes were not furnished.

## Grange

Table 30 shows the Grange home energy savings.

**Table 30: Grange – Heating and Cooling Savings – Simulation Results**

	<b>Pre</b>	<b>Post</b>	<b>Savings</b>	<b>%</b>
TDV (kTDV/ft2)	217	30	187	86%
Electricity, kWh			2214	
Natural Gas, therms			216	

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

<sup>14</sup> "The concept behind TDV is that energy efficiency measure savings should be valued differently depending on which hours of the year the savings occur, to better reflect the actual costs of energy to consumers, to the utility system, and to society. The TDV method encourages building designers to design buildings that perform better during periods of high energy cost." (E3. 2011.)

Table 31 shows the life cycle cost of the Grange retrofit package. Because the present value of the TDV savings is greater than the first cost, the benefit to cost ratio is greater than 1 and the package is cost effective.

**Table 31: Grange – Retrofit Package Life Cycle Cost**

Present Value of TDV Savings	\$28,092
Upgrade Package Cost	\$15,714
Benefit to Cost Ratio	1.8

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

Table 32 shows cost estimates for materials and installation labor for the individual measures that make up the Grange retrofit package.

**Table 32: Grange – Retrofit Cost Estimate**

Improvement	Quantity	Materials	Labor	Total
Windows	8 units	\$2,153	\$577	\$2,730
Wall Insulation	906 sq. ft.	\$1,678	\$2,537	\$4,215
Attic Insulation	852 sq. ft.	\$1,698	\$950	\$2,648
Whole House Fan System				\$341
Bathroom Exhaust Fan		\$604	\$192	\$796
HVAC Improvement		\$3,113	\$1,872	\$4,984
<b>Total</b>		<b>\$9,245</b>	<b>\$6,128</b>	<b>\$15,714</b>

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

Table 33 shows the life cycle cost of each individual measure in the Grange retrofit package.

**Table 33: Grange – Measure by Measure Life Cycle Cost**

Improvement	Cost	Savings	B/C
Windows	\$2,730	\$2,412	0.88
Wall Insulation	\$4,215	\$4,035	0.96
Attic Insulation	\$2,648	\$3,158	1.19
Whole House Fan	\$341	\$1,704	5.00
HVAC Improvement	4,984	4,588	0.92

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

The panelized Grange exterior wall was framed with 2 x 3 studs instead of the normal 2 x 4 studs used in site-built homes and had plywood sheathing on both surfaces. Because of this, it offered less space for the added blown-in insulation and a lower than normal final R-value. In addition, the wall had multi-layer foil installed in the cavity which the team estimate provided R1 average insulation. The combination of higher than normal initial R-value and lower than normal final R-value gave lower than expected life cycle cost results for the wall insulation.

## Mayfair

Table 34 shows cost estimates for materials and labor for Mayfair's Year-1 retrofit package.

**Table 34: Mayfair – Retrofit Cost Estimate**

Improvement	Quantity	Materials	Labor	Total
Windows	11 units	\$5,788	\$858	\$6,646
Wall Insulation	888 sq. ft.	\$1,674	\$2,537	\$4,211
Attic Insulation	1,104 sq. ft.	\$2,370	\$2,447	\$4,817
Whole House Fan System				\$442
Bathroom Exhaust Fan		\$604	\$192	\$796
HVAC Improvement		\$3,095	\$1,360	\$4,455
Crawlspace Improvement		\$3,500	\$2,081	\$5,581
<b>Total</b>		<b>\$17,031</b>	<b>\$9,475</b>	<b>\$26,948</b>

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Fidelia

Cost estimates for purchasing and installing these retrofits are shown in Table 35.

**Table 35: Fidelia – Retrofit Cost Estimate**

Improvement	Quantity	Materials	Labor	Total
Windows	20 units	\$6,076	\$1,677	\$7,754
Attic Insulation	1,160 sq. ft.	\$1,675	\$1,600	\$3,275
Whole House Fan System				\$676
Bathroom Exhaust Fan		\$361	\$96	\$457
HVAC Replacement		\$7,785	\$5,046	\$12,831
<b>Total</b>		<b>\$15,897</b>	<b>\$8,419</b>	<b>\$24,993</b>

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

## Caleb

Cost estimates for purchasing and installing these retrofits are shown in Table 36.

**Table 36: Caleb – Retrofit Cost Estimate**

<b>Improvement</b>	<b>Quantity</b>	<b>Materials</b>	<b>Labor</b>	<b>Total</b>
Foam Roof Insulation	1,100 sq. ft.			\$1,100
Whole House Fan System				\$830
Bathroom Exhaust Fan		\$316	\$96	\$412
HVAC		\$1,040	\$1,170	\$2,210
<b>Total</b>		<b>\$1,356</b>	<b>\$1,266</b>	<b>\$4,552</b>

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

# CHAPTER 5:

## Conclusions and Recommendations for Efficiency Retrofits

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### Conclusions

- Existing homes offer a vast opportunity for reduced greenhouse gas emissions through currently available energy efficiency upgrades. These simple, available retrofits (whole house fans, duct reconfiguration, air conditioner modification, insulation, air sealing, modern windows, etc.) are neither extensively nor properly implemented as retrofits. These envelope and heating, ventilation, and air conditioning efficiency upgrades produced an average 75 percent cooling savings in the three older homes and 52 percent on the newest house.
- The AC systems were revised to be appropriate to hot dry climates by raising the system sensible energy efficiency ratios. These revisions included: small compressors, large coils, high cubic feet per minute per ton, shorter ducts, ducts on ceiling joists and buried in insulation or moved to drop ceilings with short supply runs. The heating, ventilation, and air conditioning measures alone improved average house system efficiency by 74 percent (efficacy difference / baseline efficacy). For hot dry climates 500+ cubic feet per minute per ton airflow is required and can be accomplished through reduced tonnage, low restriction indoor coils, and a low restriction duct system.
- Shell retrofits combined with whole house fans reduced the net cooling loads by 71 percent at Grange, 63 percent at Mayfair by 32 percent at Fidelia and Caleb. The whole house fans accounted for 22 percent and 13 percent respectively of the shell reductions at Grange and Mayfair (the older houses). They accounted for 46 percent of the shell reduction at Fidelia and up to 75 percent of shell reduction at Caleb.
- In climates with large diurnal swings, Whole House Fans are very effective at reducing cooling load. Adding large amounts of attic venting is necessary with conventional Whole House Fans, but that increases the heating load in the winter
- The shell retrofits reduced heating loads in the two older houses, Grange and Mayfair, by an average of 54 percent. Shell retrofits on Fidelia netted a 23 percent load reduction, but heating loads increased at Caleb because of increased infiltration and lower attic temperatures.
- The heat pump installed as a year-one retrofit at Fidelia showed excessive parasitic electrical use from a 40-watt crankcase heater that ran most of the time and unnecessary defrost cycles. Year 2 changes to controls resolved these problems.



## Recommendations

The project team developed the following general retrofit recommendations based on this research.

- If there is little or no attic insulation
  - Vacuum, seal the attic plane with precision, and insulate after the ducts are reconfigured.
- If the ducts are hung from the rafters or go to the far walls of the house
  - Remove the ducts
  - Install new terminals near the inside walls or centered in the ceiling
  - Install new low restriction, sealed and insulated ducts on the “floor” of the attic and bury them in attic insulation
  - Increase cooling air flow to more than 500 cubic feet per minute per ton
- If there is no wall insulation
  - Drill and fill the walls with insulation
- If the house is in a climate with comfortably low nighttime temperatures
  - Install whole house fans
- If the house has single-pane windows
  - Install double-pane window, with low E2 coatings, and low conduction frames.
  - Since the air conditioner will now be oversized (and likely was previously), replace the whole unit or just the compressor with smaller size.

## ACRONYMS AND GLOSSARY

<b>Term</b>	<b>Definition</b>
AC	air conditioner
ACEEE	American Council for an Energy Efficient Economy
ACH	air changes per hour
ACH50	air changes per hour at 50 Pascals pressurization
AFUE	annual fuel utilization efficiency, a federal metric for gas heating equipment
ASHRAE	American Society of Heating, Refrigeration, Air Conditioning Engineers
BPM	brushless permanent magnet motor drive system
BTU/h	British thermal units per hour
Building Performance Contracting	A whole-building approach to identifying and addressing energy efficiency and comfort problems in a building.
Capacity shift zoning	A type of HVAC system zoning in which the zoned system never attempts to limit the delivery of capacity to only one zone, but rather prioritizes (sends more of) the air flow and capacity to the zone that is showing an increased heating or cooling load.
CBECC-Res 2013	California Building Energy Code Compliance 2013 Residential Standards compliance software
CDD	Cooling Degree Days
CFM	cubic feet per minute
CFM50	Cubic feet per minute leakage at 50 Pascals pressure
CHEERS	California Home Energy Efficiency Rating System
COP	Coefficient of Performance
CVRH	Central Valley Research Homes
ECM	Electronically Commutated Motor
EER	energy efficiency ratio
F	Fahrenheit
ft <sup>2</sup>	square foot

<b>Term</b>	<b>Definition</b>
ft <sup>3</sup>	cubic foot
GWh	gigawatt-hours, 10 <sup>9</sup> watt-hours
HDAC	Hot, Dry-optimized Air Conditioning
HERS	Home Energy Rating System (HERS), a statewide program that certifies residential energy efficiency rating services in California
HERS II	The latest version of the HERS regulation, which establishes a process for delivering whole house energy ratings for existing and newly constructed residential buildings
HP	horsepower
HVAC	heating, ventilation and air conditioning
IAQ	Indoor Air Quality
IWC	inches water column
kW	kilowatt
kWh	kilowatt-hour
low-E	Low-emissivity (low-E) surfaces emit low levels of radiant thermal (heat) energy
Mini-split HVAC system	A type of ductless air conditioner and heat pump that uses thin copper tubing to pump refrigerant from outdoor compressor and condenser unit to an indoor (typically wall-mounted) blower.
MMTCO <sub>2</sub> e	million metric ton carbon dioxide equivalent
Multi-split HVAC system	A type of air conditioner and heat pump similar to the mini-split system that can be configured so that multiple indoor units are connected to one outdoor unit.
NFRC	National Fenestration Rating Council
Pa	Pascal
P.E.	Professional Engineer
PSC	permanent split capacitor motor

<b>Term</b>	<b>Definition</b>
Residential Alternative Calculation Method (ACM) Manual	A California Energy Commission publication that contains requirements for those persons who want to design a calculation computer program for use with the Residential Building Energy Efficiency Standards.
R-value	The capacity of an insulating material to resist heat flow. Higher R-values indicate greater insulating power.
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
TDV	Time dependent valuation
Title 24 (Part 6)	California's Building Energy Efficiency Standards for residential and nonresidential buildings
U-factor	Also known as U-value. A measure of heat transmission through a building component or material. Lower U-factors indicate greater insulating properties.
USDOE	United States Department of Energy
VCSHP	Variable compressor speed heat pump
WHF	Whole House Fan

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# Appendix A:

## Internal Gains Implemented in the Research Homes

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**Table A-1: Grange Internal Gains**

Daily Internal Gains (British Thermal Units)			
Month	Sensible Added	Latent (evaporative)	Net Sensible
January	40,577		
February	38,252		
March	35,662		
April	33,082		
June	30,509	7,634	22,874
July	31,113	7,826	23,287
August	32,946	8,364	24,582
September	35,976	9,133	26,843
October	38,700	9,694	29,006
November	40,688		
December	41,144		

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table A-2: Mayfair Internal Gains**

Daily Internal Gains (British Thermal Units)			
Month	Sensible Added	Latent (evaporative)	Net Sensible
January	47,420		
February	44,623		
March	41,526		
April	38,427		
June	34,485	8,560	25,925
July	35,181	8,778	26,404
August	36,707	9,125	27,582
September	39,383	9,981	29,402
October	42,269	10,987	31,282
November	44,199		
December	48,106		

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table A-3: Fidelia Internal Gains**

<b>Daily Internal Gains (British Thermal Units)</b>			
<b>Month</b>	<b>Sensible Added</b>	<b>Latent (evaporative)</b>	<b>Net Sensible</b>
January	47,420		
February	44,623		
March	41,526		
April	38,427		
June	34,485	9,491	24,994
July	35,181	9,700	25,481
August	36,707	10,422	26,284
September	39,383	11,580	27,803
October	42,269	12,637	29,632
November	44,199		
December	48,106		

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood

**Table A-4: Caleb Internal Gains**

<b>Daily Internal Gains (British Thermal Units)</b>			
<b>Month</b>	<b>Sensible Added</b>	<b>Latent (evaporative)</b>	<b>Net Sensible</b>
January	63,219		
February	59,357		
March	55,079		
April	50,772		
July	47,122	10,834	36,287
August	50,116	11,616	38,501
September	55,099	12,940	42,160
October	59,584	14,125	45,459
November	63,760		
December	64,175		

Source: Bruce A. Wilcox, P.E.; John Proctor, P.E.; Rick Chitwood